Understanding Patterns of Growth at Kendall Square
Using a System Dynamics Approach
by
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Submitted to the Department of Civil and Environmental Engineering and Department of Urban Studies and Planning in partial fulfillment of the requirements for the degree of
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and
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Abstract

The interdependency of transportation investment and land use has yet to be fully understood to quantify the benefits of transit infrastructure. Researchers agree on the complex relationship of urban systems, particularly transport and land use, as they fail to take a holistic approach when addressing this issue. Traditional travel behavior models have a number of limitations, since they describe an equilibrium point, connecting the model inputs and outputs. In reality, however, we have to admit that there is a constant flux given the interconnected changes in transportation, land-use, and the associated policies. Public policies often fail to achieve their intended result because of the complexities of both the environment and the policy making process. It is argued that, in order to understand the sources of, and the solutions to, these issues, linear and mechanistic thinking must give way to non-linear, systems thinking. System Dynamics, a methodology that emerged in the 1960s with the work of Jay Forrester and his colleagues at the Massachusetts Institute of Technology (MIT), has been utilized in this thesis to address these complex issues.

This System Dynamics approach simultaneously models land use and transportation systems in the Kendall Square area. The model is based on the causality functions and feedback loop structures between a large number of physical, socio-economic, and policy variables. This perspective confirms that a combination of job opportunities, employment density, accessibility, changes in mobility patterns, agglomeration of industries, and proximity to MIT has made Kendall Square a unique location in the Boston area. Hence the interest on identifying the specific dynamics and interactions that exist in the area, to examine the limits of growth. The System Dynamics model built consists of 4 sub-models: population, employment, housing, and travel demand.

While this is a first attempt at using System Dynamics to model the interaction between transport and land use in Kendall Square, the model development and application are limited due to data availability and the research scope. However, the results indicate that the proposed method is a promising approach to deal with complex land use development and transportation. The model shows how a system’s approach can yield accessible, insightful lessons for policy making, stemming from the endogenous and aggregate perspective of system dynamics modeling and simulation presented here.

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To all my friends in room 1-151 and fellow colleagues in the MST and MCP programs for the late nights, interesting conversations, and friendship.

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To all my friends, thank you for your love, constant encouragement, but most of all for keeping me balanced.

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Modeling, as part of the learning process, is iterative, a continual process of formulating hypotheses, testing and revision, of both formal and mental models...

A good modeling process challenges the clients' conception of the problem...

As a modeler you have an ethical responsibility to carry out your work with rigor and integrity. You must be willing to let the modeling process change your mind.

John Sterman, Sloan School, MIT
1. Introduction

Transportation changes take place in a highly dynamic environment. Changes continue after transportation investments take place, making it difficult to attribute observed changes correctly to underlying causes. Therefore the market response to changes in transportation may still take place after many years or even decades. As a result, it is difficult to identify transportation investment impacts on land use. Some argue that land use changes may appear before the project is actually constructed, because landowners may act in anticipation of higher land values. However, as the time span of these effects increases, it is even more difficult to isolate changes resulting from transportation impacts from all the other changes.

One can hypothesize that transportation infrastructure, in particular rail transit, is a facilitator of development, not a cause. Under such a view, transportation is a necessary but not a sufficient condition for development to occur. Transport schemes and projects are often sponsored on the grounds that they will help regenerate a city or town's economy. This is a popular theme, but while common sense suggests that good transport must be related to economic activity and growth, in practice it is much harder to demonstrate the nature of the connection since evidence of such relationship is far from clear. Transit investment is but one piece of the equation, since local land-use policies, together with other government policies, local and regional economic climate, among others may interact reinforcing the probability of land development changes. On the other hand, local zoning practices and political attitudes may constrain development intensification, thus reducing the impact of transit investment on land values. The topic has of course been researched and models have been developed over the years to understand such relationships.

Most researchers agree that urban economies are complex systems; however they generally do not consider and use systems models to try to understand these complexities. In parallel, traditional travel behavior models have a number of limitations, essentially because the available data only reflects the final state, which from the aggregate standpoint, appears as an equilibrium point, even when it is apparent that the problem is essentially dynamic. In fact, changes in behavior in response to various stimuli are not instantaneous but take place over long periods of time and delays. Theoretically, it is possible to introduce dynamic interactions into the traditional four-step modeling process; however, the introduction of this type of feedback is usually not considered because the unwieldy nature of the calculations results in excessive complexity (Ortúzar and Willumsen 1994, Raux 2003).
Transportation changes take place in a highly dynamic system, particularly because:

- A change in this system is just one of many changes occurring at the same time;
- Changes continue after transportation investments take place, making it difficult to attribute observed changes correctly;
- These interactions take place over time.

As a result of systems delay, it is difficult to identify transportation investment impacts on land use. As the time span of these effects increases, it becomes even more difficult to isolate changes resulting from transportation impacts from all the other changes.

The interaction among feedback loops, the complexity of reaction mechanisms, and the non-linear relationships among variables justify the use of systems dynamics simulation tools, a modeling approach which dates back more than 40 years with the pioneering work of Jay Forrester. This approach has been widely used in transportation, especially for aggregated long-term scenarios, as well as for forecasting, and modeling interaction between land use and transport. Supporters of this technique not only criticize traditional models because they are technically inefficient, but also because they fail to address the central issue – "that our major towns and cities are in states of constant flux, the product of many interacting forces acting on short and long time spans with feedbacks also operating on many time scales" (Swanson 2008).

A system's approach allows for decision makers to understand the connection between different systems. It also provides the means of representing the key performance drivers, and their interdependencies and interactions, within dynamically complex environments. Several elements of the system dynamics method that enable this to be achieved include: (1) cause and effect relationships, (2) representation of feedback loops, (3) time-delayed responses, (4) non-linear responses, (5) and representation of decisions rules.

1.1. Motivation

In the last decade, Kendall Square has been booming economically and as a result has attracted a number of companies, including Microsoft and Google, due to its unique environment and proximity to the Massachusetts Institute of Technology (MIT), which brings in the latest technology and research while offering a pool of skilled individuals. This high-tech mecca is in the process of blossoming into a bona fide neighborhood. Since 2006, more than 1,700 residential units have been built in and around Kendall Square, making it Cambridge's fastest-growing residential area, albeit
an expensive one. Kendall Square's residential growth has been “dramatic” in recent years, based on the number of new housing units. As more people choose to live in the square, growing numbers of restaurants and other businesses are catering to the resident’s needs. Growth in the area has brought an increase in the number of commuters to the square, both motorized and non-motorized.

Undoubtedly, a large part of the success of Kendall Square results from the availability of transit services and the overall increase in accessibility which resulted from the expansion of the MBTA Red Line in the 1980s. Nevertheless, this is just but one piece of the equation. Automobile accessibility, maximum parking policies, land use and zoning regulations, housing developments, and agglomeration benefits of economic activities interactions, have been key factors in the success of this square.

As the transport infrastructure reaches its capacity limits and no operational changes are scheduled for the near future, land is becoming scarce, and business development is outweighing housing development, it is crucial to understand the dynamics of changes and the limits of growth in the area. Looking into the future, if Kendall Square wishes to foster more growth, it is critical to gain a better understanding of the relationship between various sectors (housing, employment, transport, etc.) and the effects of certain policies over long periods of time. Understanding the “big picture” not only allows for identifying compounded effects, but also existing constraints in the system, overshoots, delays, and collapses as capacities are reached.

1.2. Research Questions and Approach

The relationship between transportation and land use has often been described as a “chicken-and-egg” problem since it is difficult to identify the triggering cause of change – do transportation changes precede land use changes or vice-versa? In order to address the multiple and complex dynamics that exist in urban systems, a system dynamics model will be developed to understand the transformation of Kendall Square. This transformation will be tracked through the last 20 years, allowing for the development of historical patterns and the identification of major causal loops that allowed for the success of the square and for the temporal response of change in land use to transportation changes. Particularly, this model aims at simulating the interactions between transport and the wider social and economic activities observed in the area.

The model will borrow from Forrester's Urban Dynamic Model (Forrester 1969) and from several other models already developed and found in the literature. In addition, it will include concepts
such as accessibility to destinations and attractiveness of a zone as a place to live or to do business. It will also identify causal relationships between several sub-systems (population, employment, infrastructure, zoning policies, etc.) that have been observed and may explain the success of Kendall Square. Data for the different variables will be obtained from the Census Bureau, the Central Transportation Planning Products (CTPP), other studies in the Kendall Square area, and literature.

Specific questions for this research are outlined below:

- What are the specific dynamics and interactions that exist between transportation and land use?
- Did Kendall Square development happened by chance?
- Has employment density and growth been caused by increasing the accessibility of the Kendall Square area, particularly transit accessibility? Has residential density played an equal role in such success?
- Can the continuous growth observed in the area be sustained in the future? Are there specific sectors (housing, employment, etc.) which will limit additional growth?
- Do excessive parking, congestion, and lack of additional transit capacity threaten its future growth?
- What policies, on the long-run, may constrain current patterns of growth?

1.3. Contributions

As mentioned, the purpose of this modeling framework is to obtain a holistic view of the dynamics that occur in Kendall Square. This framework, in the end, aims at understanding the patterns of growth and the constraints to growth by obtaining relative measures among variables, which will enable the analysis of patterns over time and the testing of difference scenarios.

A system’s approach will illustrate how the feedback structure of the system can endogenously generate growth, stagnation, and decay. Understanding the causalities and temporal responses to different policies will help in allowing for continuous growth in the area and in possibly replicating the success in other areas, particularly around future Green Line stations.
1.4. Thesis Structure

This thesis is composed of seven chapters, including the introductory chapter. Chapter 2 will present the literature review of previous work done on the relationship between transportation and land use, particularly looking at densities, proximity to transit stations, and transit investment. In addition it presents the concept of agglomeration theory and the benefits of agglomeration around transit stations. Chapter 3 explains why a system dynamics approach is appropriate in answering the research question as defined, by providing background for the field of System Dynamics as well as some examples of applications of System Dynamics to the field of transportation industry.

Chapter 4 provides an overview of the general trends observed in the city of Cambridge in the last 30 years and provides further insight on the particular changes observed in the Kendall Square. This chapter includes some analysis done by Peralta-Quirós (2013), a graduate student at the MIT, who is also examining the history of Kendall Square and running a regression analysis in order to provide a better understanding of the accessibility, employment and commuter pattern changes that have taken place in the area.

Chapter 5 introduces a preliminary analysis, which entails a conceptual System Dynamic model and includes an explanation of the key feedback loops. This chapter allows the reader to effectively interpret the computable model contained in the subsequent chapter. Chapter 6 presents the specified analysis, which translates many of the concepts discussed in the previous chapter into an appropriate variable format, functional relationships, and input parameters. The chapter also includes discussion and justification for key assumptions and supporting evidence for variable relationships and initial parameters, which are provided when appropriate, depending on availability. Chapter 7 provides a comprehensive analysis of the model built for the Kendall Square area, which includes the validation and calibration of the model. It provides specific conclusions drawn from the output of the model, which result from the dynamics of change observed in Kendall and their implications for growth over time. The second half of the chapter presents a sensitivity analysis for some of the parameters, as well as several policy applications.

Chapter 8 provides a summary of the study presented in this thesis, in addition to some limitations of the work, further research, and opportunities to improve the model.
2. Literature Review – Land Use and Transportation Connection

This chapter is intended to provide the reader with existing research on the relationship between transportation and land use. The effects of land use on transportation and vice versa are explored particularly the effects of employment and population densities together with proximity to transit on ridership. Lastly, the chapter explores theories on agglomeration and why certain firms decide to locate near transit stations.

2.1. Transportation and Land Use Interaction

The relationship between transportation and land use has long been acknowledged within academic disciplines such as economics, geography, and urban planning, as well as by the general population. That the spatial separation of human activities creates the need for travel and goods transport is the underlying principle of transport analysis and forecasting. Though the interaction and influence of urban land use and transportation are known, it is common practice for planners in both domains to prepare plans without due consideration for this interaction. In fact, the integration of land use and transportation systems is important because they enable policy makers to foresee and evaluate the effects of transport and urban plans jointly thus providing solutions to common planning problems.

Transportation networks and the spatial patterns of land use they serve are assumed to mutually influence each other over time. Transport system improvements (e.g. new or improved transport infrastructure) lead to an increase in accessibility at certain locations, which leads in turn to a change in the value of land at those locations. This change in value at locations provokes a change in land use patterns. Furthermore, changes in the number and distribution of opportunities and activities lead to changes in travel patterns, affecting the transportation system in such a way that the cycle replicates itself. This interaction is also influenced by other factors such as public and economic policies (e.g. taxation, fuel prices, and zoning regulations) and exogenous events (e.g. major natural disaster). The recognition that trip and location decisions co-determine each other and therefore, that transport and land use planning need to be coordinated led to the notion of the "land-use
transport feedback cycle (Wegener and Fürst 2004). The relationship between land use patterns and transportation is best represented as a cyclical connection displayed in Figure 2.1. The set of relationships implied by this feedback cycle can be briefly summarized as follows:

- The distribution of land uses, such as residential, industrial or commercial, over the urban area determines the location of human activities such as living and working, shopping, education or leisure.
- The distribution of human activities in space requires spatial interactions or trips in the transport system to overcome the distance between the locations of activities.
- The distribution of infrastructure in the transport system creates opportunities for spatial interactions and can be measured as accessibility.
- The distribution of accessibility in space co-determines the location decisions and so results in changes of the land-use system.

Figure 2.1 Transportation and Land Use Interaction (Hanson and Giuliano 2004)

Most transportation-land use theories and models are essentially static as they explain land use patterns - they do not explicitly consider the processes that are creating or changing them; they assume instantaneous equilibrium across all markets (Rodrigue, Comtois, and Slack 2009; Hanson and Giuliano 2004). However, both components (land use and transportation) are part of a dynamic system that is subject to external influences. It is to be noted that each component of the system is constantly evolving (at different rates) due to changes in technology, policy, economics, demographics and even cultural values. For example, employment changes relatively rapidly, as old
jobs are eliminated and new ones emerge, and as firms move or grow, or go out of business. However, the built environment changes very slowly. For example, major highway or rail projects take years to build and have an operational life of many decades. It is therefore likely that metropolitan areas are never in equilibrium, but rather constantly adjusting to the changing employment and population dynamics. According to Polzin, the impacts of transportation investment on land use can be characterized in a three-tiered response. The first is by providing transportation accessibility, the second by encouraging complementary investment policies, and the third by creating momentum for expectations that influence land use. However, most theory and modeling focus almost exclusively on trying to define the first relationship (Figure 2.2) (Polzin 1999).

![Figure 2.2 Transportation Impact on Land Use (Polzin 1999)](image)

### 2.2. Effect of Land Use on Transportation

Erwing and Cervero conclude that land use patterns have a modest but often statistically significant effect on transportation behavior. As they point out, many studies on this question fail to consider causality: an observed relationship between, for instance, density and vehicle miles traveled could be caused by people who prefer transit, choosing to settle in higher-density neighborhoods, rather than neighborhood density actually changing the travel behavior of residents (Ewing and Cervero 2010).

The extent of a relationship between land use and transportation behavior varies by different components: trip length, trip frequency, and mode choice (Kolko 2011). Of these components, trip length and mode choice are most affected by local land use patterns, while frequency is determined primarily by household socioeconomic characteristics (Ewing and Cervero 2001).
Among measures of land use patterns, two measures of accessibility – job accessibility by auto and distance to the downtown area – have the strongest relationship to miles travelled (Ewing and Cervero 2010). In other words, people who live closer to jobs or other destinations logically drive less. The relationship between proximity to jobs and VMT is strongest when proximity is defined as the availability of jobs within four miles of home (Cervero and Duncan 2006). In addition, Erwing and Cervero (2010) examined the relationship between residential and employment density and found a weak relationship with VMT, while controlling for various design attributes of street networks, which could further reduce VMT by encouraging walking and transit trips.

The Transportation Research Board (TRB, 2009) concluded that doubling residential density would lead to a 5-12 percent reduction in VMT, and possibly up to a 25% reduction with complementary changes in transit availability, the job-housing balance, and other factors (Gomez-Ibanez et al. 2009). The research literature suggests that integrated policies – including both land use and transportation components – have a greater effect on VMT than land use policies alone. The TRB report also tested a scenario of higher density plus complementary changes like transit availability that would lead to twice as large a VMT reduction as the upper-bound estimate of higher density alone (Gomez-Ibanez et al. 2009).1 A review on modeling studies shows that transit policies alone (like transit improvements) resulted in a median VMT reduction of 0.9% over 20 years; land use policies alone (like increased densities) resulted in VMT reduction of 1.1%. However, combined land use/transit policy scenarios resulted in a median VMT reduction of 8.1%. In other words, the estimated result of integrated policies was far greater than the sum of the individual policies on their own (Rodier 2009). The researcher notes that the synergy appears to be due to policy coordination, not just methodological differences in the model.

### 2.2.1 Densities Around Transit Stations: Employment vs. Population

Research on land use patterns and their relationship with transportation has focused primarily on residential land use rather than on commercial land use (including industrial, retail, and office). Residential density around transit nodes, residents' travel patterns, and residential land use receive

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1 The committee developed two scenarios since they disagreed on how large an increase in residential density would be feasible. In the first scenario, 25% of new residential development would be twice as dense as typical new development, and residents of new developments would reduce VMT by 12%, which results in a decrease of roughly 1.5% in the overall VMT from 2000-2050. In the second scenario, 75% of new residential developments would double their density, and residents of these new developments would reduce VMT by 25% with an overall VMT reduction of roughly 10% over the same time period.
more attention in the research and policy literature than employment density, worker's travel patterns, and commercial land use do. This is due in part to the availability of data for small geographic areas, making it easier to measure patterns and trends in residential land use. A second reason for this disparity is the classic land use model found in economic and planning literature. The monocentric city model assumes all employment to be at the city center and that people make residential decisions based on commuting distance from their downtown jobs, the cost of housing, and other factors.

However, recent research has challenged the traditional emphasis by arguing that the location of employment matters critically to transportation behavior. Employment densities and workplace proximity to transit are at least as important as residential patterns for achieving transportation goals. In theory, proximity to the workplace should matter more than residential proximity to transit because "unlike the home end of trips, where there are many options for accessing transit, generally, walking is the only available option at the work end" (Barnes 2005). Accordingly, employment densities at trip destinations affect ridership more than residential densities at trip origins (Kolko 2011; Peralta-Quirós 2013).

In fact, a study conducted by the Public Policy Institute of California in 2011 (Barbour and Teitz 2006) confirms that, across all metropolitan areas in the United States, those with higher density have higher transit ridership, but the magnitude of the relationship between employment density and transit ridership is twice as large as that between residential density and transit ridership. Furthermore, metropolitan areas where employment is more centralized in downtowns have higher transit ridership, even after taking residential and employment density into account.

It is important to emphasize that public transit is a critical part of the economic and social fabric of metropolitan areas and that transportation networks are critical for the region's economic competitiveness. Concentrating future employment growth in higher density mixed-use districts promotes more sustainable and equitable regions. The location of jobs in auto-oriented suburban communities at the edge of metropolitan regions, results in significant costs to households and individuals as they spend more time and money commuting to work. From an environmental perspective job sprawl results in an increase in land consumption, greater pollution, and greenhouse gas emissions. Transit is seen as a central mechanism for facilitating increased densities in the core, countering dispersal trends.
2.2.2 Proximity to Transit and Ridership

Just as transit ridership varies across metropolitan areas, ridership varies within metropolitan areas, given that proximity is an important factor. Transit ridership diminishes rapidly as distances from transit stations increases. That is why most studies in transportation behavior use either one-quarter or one-half mile as the distance from a station that affects mode choice (Untermann 1984; Kolko 2011). However a study on the relationship between transit oriented development and ridership in California determined one-half mile as the distance within which residents' transit ridership differs from residents elsewhere on average (Cervero 2007). In addition, Cervero found that residents on developments built near transit are more likely to commute by transit even if their workplaces are one mile from transit.

Some facts that underscore the importance of locating transit near jobs and encouraging job growth near transit are:

- Transit ridership depends on proximity to transit, especially workplace proximity.
- Employment density is more strongly associated with transit ridership than residential density is.
- Employment densities at trip destinations affect ridership more than residential densities at trip origins.

2.3. Effects of Transportation on Land Use

Just as land use patterns influence transportation behavior, transit investments have the potential to influence land use outcomes, including land values and densities. For example, transit investments could rise nearby property values if the increased accessibility raises demand in the immediate area for residential and commercial space. This increase in demand could in turn, lead to higher residential or commercial densities in the absence of constraints on development. At the same time, land values could fall if transit and other developments create problems such as congestion and noise.

The relationship between transit and land values and densities depend not only on how businesses and residents value the proximity to transit, but also on the public sector decisions about zoning, land use, and other economic incentives. According to Giuliano and Agarwal's study, which reviewed numerous reports on land use patterns around transit stations, "rail transit does not consistently lead to significant land changes", and the land use changes that do occur are facilitated
by complementary land use policies like development incentives and stringent parking management policies (Giuliano and Agarwal 2010).

2.3.1 Transit Investment and Reduction of Vehicle Miles Travelled

Even though transit availability is associated with higher transit ridership for nearby residents and workers, the effect of transit investment on the reduction of auto trips depends on numerous factors. Reasons that may explain this include:

- Rail investments tend not to increase overall transit ridership in most cities; rather, most rail transit commuters are former bus commuters, not former drivers, and the main effect of rail investment may be giving transit users a faster transit option rather than reducing VMT. For example, from 1990 to 2008 the share of fixed-line transit commutes (rail, subway, and streetcar) rose by 0.21% for the overall nation while the share of other transit commutes (primarily bus) decreased by 0.26% (Kolko 2011).

- Downs' "fundamental law of highway congestion" suggests that road expansions are met with proportional traffic increases. Studies have shown that road investments raise VMT proportionally, while provision of public transportation has no effect on aggregated VMT (Duranton and Turner 2009).

- Transit investments are typically aimed to serve commutes, which occur at peak times on most congested routes, but commuting accounts for only a portion of total VMT. Non-commute trips like those to stores, school, and family or social events are much less likely to use transit than commuting trips. Thus, increased transit investment and commute ridership could displace only a fraction of the VMT.

Though transit investment may not reduce overall vehicle miles travelled, public transit investment may be desirable for other reasons, not least for expanding transportation options without raising VMT as much as road expansion would. New transit investments can raise the share of residents and workers close to transit in two ways: (1) by locating transit in high density areas, (2) and by encouraging greater densities around new transit stations. Areas with high density neighborhoods can support fixed-line transit such as subways, rail, and streetcars, because density provides the ridership needed to make such systems economically feasible. In addition, increasing density around new transit stations depends on both public and private sector decisions that encourage or discourage development, including zoning, urban design, and investment decisions. Therefore,
patterns of development around new transit nodes affect the extent to which transit investments lead to greater transit ridership and therefore the reduction of auto trips (VMT).

2.4. Agglomeration Theory and Transit Ridership

As mentioned, transit ridership and density have an inherently symbiotic relationship. Transit systems are especially well-equipped to address the needs of commuting trips. This is due to a combination of three major components of the home-work transit trip: system design, location decisions of employers, and location decision of workers.

- **System Design** – The majority of older transit systems were designed primarily to bring residents from outlying neighborhoods and cities into the downtown of the central city. While newer systems have concentrated on connecting multiple destinations throughout the region, most still tend to link most strongly to downtowns. Central business districts, which have both the largest density of jobs in most regions and the highest quality of transit services are also typically the least amenable to automobile access, with limited and/or expensive parking and significant traffic congestion. Thus, making transit a natural fit for the commute trip from the suburbs to the central business district area.

- **Location decisions of employers** – There are myriad considerations affecting a firm's location decision. These include land and building prices and availability; proximity to production inputs, to customers, and to complementary firms; neighborhood amenities and support services; and a host of other factors. For some firms, the benefits of density dictate a location in the downtown and in other types of urban employment centers; the existence of transit access may be a secondary consideration. For other firms, however, labor may be the most critical input into operations and, consequently, access to a talented, high-skilled labor force is of critical importance and a central location near transit may be essential for maximizing the ability to draw from this pool.

- **Location decisions of workers** – As with employers, residents decide where to live based on a vast array of factors, including home prices, amenities (both of the home and of the surrounding neighborhood), services, and a number of other highly idiosyncratic variables. However, ease of access to commonly visited destinations is often among the most important considerations in this decision. As such, for those that work (or may, in the future, work) in transit-accessible locations, its proximity to high quality transit may be an important factor in deciding where to live.
Greater densities at station areas create a large market for workers, residents, or customers that can easily access transit; similarly high transit ridership creates an incentive for businesses, services, and residents to locate at greater density areas. While these factors are deeply related, however, each has a different set of potential benefits to industries, which may vary across sectors. The ability of policymakers to reverse trends of job sprawl and to incentivize concentrations of employment near transit depends in part on leveraging the natural tendency for certain industries to agglomerate, or concentrate at these nodes.

Several studies have attempted to quantify the effects of agglomerations, particularly the effects of productivity gains by agglomeration of industries (Peralta-Quirós 2013; Graham 2007). Some studies indicate that some types of firms may have a preference for higher-density urban locations, and can benefit from agglomeration. A 2011 study by the Brookings Institution (Tomer 2012) found that, for the 100 metropolitan areas considered, workers in some industries enjoy far better access to transit than others. Those working in finance, insurance, and real estate – all jobs typically located in downtown areas – were shown to have the highest transit job coverage. The study showed that of all employment categories, manufacturing jobs were the most suburbanized, with 77 percent located more than five miles from city centers; by contrast, skill-intensive jobs were the least suburbanized, at 67 percent.

Another study, by the Center for Transit-Oriented Development (Belzer, Srivastava, and Austin 2011), suggest that the sectorial mix of jobs within a station area skewed to more knowledge based firms when station areas have higher employment densities. Knowledge-based industries show 45 percent of jobs in transit zones with very high employment density, compared to only 15 percent in very low density transit areas. Similarly, public sector employment also comprises a higher share of the industry mix in higher density station areas. However, retail production, distribution, and repair employment declines as the area's employment density increases.

Agglomeration literally means “to mass together” and refers to the process through which firms, acting independently, decide to locate in close physical proximity to each other. Locating among large groups of firms – whether similar or unrelated – is said to confer benefits to the individual firms, collectively known as “economies of agglomeration”. An extensive amount of research has been performed to understand the benefits of agglomeration as well as the sources and effects.

- Geographical Proximity - Firms and industries choose to concentrate as a method of mitigating transport costs. Firms are likely to make site location decisions that minimize
transport costs from suppliers, as well as to minimize distribution costs to consumers. The site locator perspective inherently leads to industry agglomeration as firms within specific industries are driven by these benefits. This agglomeration is further reinforced through potential co-location, creating new economies of scale, from intermediate suppliers who wish to take advantage of existing agglomerations.

- **Labor Market Pooling** – At the firm level, agglomeration economies provide firms with the ability to attract knowledgeable and skilled workers from an existing workforce. Access to an experienced workforce provides firms with the ability to access potential employees without spending substantial amounts of resources on recruiting and hiring processes.

- **Knowledge Spillover** – The transference of information and knowledge intensifies with increased geographical proximity among firms. This transfer of knowledge occurs in a variety of transactions that can take place within institutions such as formal business relationships as well as with more informal spillovers such as imitation. Currently, economists attempt to understand the relation between innovation and agglomeration. According to Belzer (2011), it is in dense urban environments where the vast majority of substantial innovations emerge. The benefits of geographic concentration favor technological, organizational, and commercial innovation.

As mentioned earlier, employers may benefit from agglomeration in transit areas because they can take advantage of expanded access to the pooled workforce. In recent years, this pooled workforce not only includes the *transit-dependent*, but also the *transit-dependent-by-choice*. This later group, which includes a large number of your workers in knowledge-based sectors, prefer to live in more pedestrian- and bicycle-friendly urban areas as to not drive is a lifestyle choice (Belzer, Srivastava, and Austin 2011). By accessing a larger, higher quality of labor pool, employers may be able to attract and retain higher quality workers. In addition, because these workers often choose to live in more “walkable” places where informal social encounters are more likely, access to transit may also facilitate knowledge spillovers. Each of these, in turn, are more likely to increase profitability and productivity.
We can conclude that economic competitiveness requires connections and accessibility: for a region to be economically competitive, employees with the right skills need to be able to reach appropriate employers in a reasonable time and at an affordable cost.
3. Thinking in Systems

The concept of thinking in systems was developed in the fifties as a method to deal with problems in complex systems (Forrester 1969; Sterman 2000). It is a conceptual and analytical approach based on understanding connections and relationships between seemingly isolated events. In technical terms, system thinking is defined as achieving understanding on relationships and patterns among elements in a network of relationships. The essential properties and behavior of complex systems are derived from internal relationships.

3.1. Traditional Transportation Modeling

Modeling is used as a planning tool to evaluate many different scenarios and test for key sensitivities which can act as policy levers. In transportation, planning models are required to generate insights and aimed at enhancing the understanding of the complex, long-term intra- and interrelations among the transport system and other related systems.

Most transportation model outputs are produced in a deterministic manner, because of the uncertainties in the estimation of input data and modeling parameters, and outputs are bound to an uncertainty range. To date, and for a variety of reasons, some forecasting models have had high margins of error. These errors are attributed to: (1) errors in the existing or collected data; (2) difficulty in modeling human behavior; and (3) the uncertainty of the future (Hernández 2011; Sterman 2000). In addition, in most transportation studies, land use, socioeconomic, and demographic forecasts are obtained using separate modeling techniques, which are then used as exogenous external inputs into transportation models. These ultimately result in inconsistencies and incompatibilities in the modeling procedures, leading to inaccurate results, given that the interaction between transportation, land use, and socioeconomic structures is often ignored.

Traditionally, transportation planning models are used to forecast levels of traffic or transit ridership at a given point in time. Best practice in travel forecasting – the equilibrium approach – attempts to simultaneously (or iteratively) solve for travel demand given a congested network and to estimate network congestion given the travel demand. However, in reality, at no point in time is the demand/supply system actually in perfect equilibrium given that individuals and firms continuously enter and leave the system. Changes in system performance, such as reducing the number of vehicles per household, the travel times between places, lead to further changes in user behavior, such as choice of route and mode, departure time, sequence of trips, or destination. Some
of these behavioral changes are made readily with only a short time lag. The disruptive nature and high transaction costs of others, such as switching jobs or moving to a new residence, mean they are rarely modeled. Therefore, the real system is never in equilibrium; the equilibrium point is continuously shifting as different components of the system interact. Hence the need for a "dynamic" approach.

3.2. System Dynamics Modeling (SDM)

3.2.1 Origin and Purpose

System Dynamics originated in the 1960s with the work of Jay Forrester and his colleagues at the Massachusetts Institute of Technology (MIT) as an attempt to address dynamically complex long term policy issues in the public and private domain (Sterman 2000). Jay Forrester developed the initial ideas by applying concepts from nonlinear dynamics and feedback control theory to the study of industrial systems. One of the best applications of the new ideas was Forrester’s Urban Dynamics, in which he explains the rapid population growth and subsequent decline observed in cities like Manhattan, Chicago, and Boston (Ford 2009). Forrester viewed the city as a system of interacting industries, housing, and people, which would grow rapidly under favorable conditions. However, as its land area filled, the city would shift into stagnation characterized by aging housing and declining industries, which would eventually lead to a decline in population. Forrester’s specific findings and policy recommendations were controversial and not generally agreed upon today, though researchers in the field still acknowledge the need to use this type of modeling technique (Sanders and Sanders 2004; Swanson 2008; Hernández 2011b; Abbas and Bell 1994). According to Coyle, System Dynamics is a method of analyzing problems in which time is an important factor, and which involves the study of how a system can be defended against, or made to benefit from, the changes and shocks which fall upon it from the outside world (Coyle and Goad 1986).

The “dynamics” in System Dynamics are the fundamental patterns of change, such as growth, decay, and oscillations. So SDMs are constructed to help us understand why these general patterns occur. But it is important to highlight that they are not constructed to predict the exact value of the system at a specific time in the future. The main objective of SDMs is to understand how and why the dynamic trends of concern are generated and to search for management policies to convert or improve the system’s emerging trends and its causes.
It is said that the real world is a multi-loop, multi-state, nonlinear feedback system that reacts to the decision makers' actions in ways both anticipated and unanticipated. That is, the effects of our actions can appear at a distant point in time and space and even with unintended consequences. The elements of dynamic complexity that masks our individual and organizational decision making skills are typically classified as: feedback, time delays, and nonlinearity.

3.2.2 Policy Resistance

Policy resistance occurs when policy actions trigger feedback reactions from the environment that undermines the policy and that at times even aggravates the original problem. Policy resistance is common in complex systems characterized by many feedback loops with long delays between policy action and its consequences. In such systems, learning is difficult and actors may continually fail to appreciate the full complexity of the systems that they are attempting to influence. As Forrester (1969) notes, because of policy resistance, systems are often insensitive to the most intuitive policies.

As Sterman (2000) writes, most of the changes we now struggle to comprehend arise as consequences, intended and unintended, of human actions. All too often, well intentioned efforts to solve pressing problems lead to policy resistance, where our policies are delayed, diluted, or defeated by the unforeseen reactions of other people or of nature. Meadows (2008) describe policy resistance as the tendency for interventions to not reach their intended effect due to the response of the system to the intervention itself. Attempts to stabilize the system may destabilize it; decisions may provoke reactions by others seeking to restore the balance upset in the first place. Forrester calls this phenomenon the "counterintuitive behavior of social systems".

A System Dynamics approach allows for decision makers to view causal relationships outside the sequential organization of traditional mental models of the world, and over time horizons that are largely too far reaching for decision makers to intuitively understand, "since effects are not necessarily immediately preceded by their causes in time and space" (Sterman 2000). Understanding the dynamics that exist between systems, particularly the delays and feedbacks, allow us to become better equipped to make decisions less prone to policy resistance. Much of the art of system dynamics modeling is discovering and representing the feedback processes, which, along with stock and flow structures, time delays, and nonlinearities, determine the dynamics of a system.
3.2.3 **Limits and Delays**

In the real world, some systems may not grow infinitely. For example, housing and employment growth are constrained by availability of land. Without any limiting factor, housing and employment can grow exponentially, but all systems are inherently equipped with equilibrating loops that prevent infinite growth. As Meadows writes: "A growing physical entity will stop exactly at its limits only if it receives accurate, prompt signals telling it where it is with respect to its limits, and only if it responds to those signals quickly and accurately" (Meadows 2001).

In the case of transportation systems, the findings of Pushkarev and Zupan (1977) suggest there is a limit of 150,000 end trips per square mile in areas solely by auto. Therefore, in order to obtain additional growth and provide accessibility to a larger number of end trips, a city must provide additional transit accessibility.

In real world systems, time delays are extremely impactful in our ability to make decisions and assess the efficacy of those systems. Time delays affect the ability of decision maker's to identify and isolate cause-and-effect relationships, as there are many contributing factors influencing the system. Even if decision makers were able to identify such causality, incorporating that feedback from the system into the next decision cannot be done until the feedback has been received. But unfortunately, sometimes, the received feedback is no longer relevant to the current decisions being made.

3.2.4 **Causal Relationships**

All dynamics arise from the interaction of just two types of feedback loops: positive (or self-reinforcing loops) and negative (or goal-seeking) loops. The positive loops generate exponential growth, while the negative loops reverse the direction of change or try to pull the system into balance or equilibrium. As Forrester says "The urban system is a complex interlocking network of positive and negative feedback loops. Equilibrium is a condition wherein growth in the positive loops has been arrested" (Forrester 1969). Though there are only two types of feedback loops, models may easily contain thousands of loops, of both types, coupled to one another with multiple time delays, nonlinearities, and accumulations or stocks. Intuition may enable to infer the dynamics of isolated loops, but when multiple loops interact, it is not so easy to determine what the dynamics will be.
John Sterman (2000) claims that accurate mental simulation is nearly impossible, that "people cannot simulate mentally even the simplest positive feedback system, the first-order linear positive feedback loop," and this is particularly true and evident in the poor understanding of exponential growth that results from many of the reinforcing loops. The problem is rooted in the fact that our logical capacities do not serve us well in the world of complex systems, in which there are many barriers to the typical methods of learning. The significance of this limitation is that many causal relationships display a disconnection between the linearity of the input and the non-linearity of the response, a significant distinction to be made in assessing systems (Hernández 2011).

### 3.2.5 Non-linear Responses

Aside from time delays, many real cause-effect relationships are characterized by non-linear responses, as the effects are rarely proportional to their causes, and what happens locally in a system (near the current operating point) often does not apply in distant regions (other states of the system). Nonlinearity often arises from the basic physics of systems, but also arises as multiple factors interact in decision making.

### 3.3. Transportation and System Dynamics

Dynamic simulation can capture and quantify two issues at the core of transportation planning: the changes over long periods of time and the nonlinearity that is so characteristic of the environment and extremely difficult to intuitively comprehend. Common practice in the field is to plan and assess the success of transportation investment at one point in time, in a way that fails to fully capture how earlier decisions affect later decisions. As discussed, this is a one-dimensional approach for a system which is constantly evolving. In addition, due to the nonlinearity of complex systems driven by reinforcing and balancing feedback loops, important decisions taken sooner rather than later will be much more impactful in the long term, particularly when other decisions are triggered as a result. In fact, when positive loops are at play, their combined impact is often larger than the sum of their parts (Sterman 2000).

As Hernández (2011) points out, although every system is subject to constraints, it is less common in transportation systems to be constrained by "good" balancing feedback loops and more common to be limited by the "bad" balancing feedback loops. For example, an increasing demand most likely means that the system is performing well, given the limited resources (physical capacity constraint). However, declining demand for transportation services (regardless of capacity
utilization) is a less ideal way for the system to be limited and much more difficult to "counteract as behaviors, attitudes, and other human dynamics propagate through the system" (Hernández 2011)

Though transportation systems are planned and funded on a link-by-link basis, these types of systems are entirely dependent on network performance and, as pointed out by most researchers in the field, is a prime example of a system that collectively is worth more than the sum of its parts. In practice, there are modeling techniques that are used to forecast volumes of travelers, attractiveness to destinations, accessibility, and productivity, amongst others at the operational level, using a high level of detail that is less useful for high-level strategic decision making scenarios.

3.3.1 Benefits and Limitations of System Dynamics

The application of system dynamics to transportation is well documented in the literature (Armah, Yawson, and Pappoe 2010; Abbas and Bell 1994; Wang, Lu, and Peng 2008; Egilmez and Tatari 2012; Young, Thompson, and Taylor 1991; Pfaffenbichler, Emberger, and Shepherd 2010; Hernández 2011; Raux 2003; Galicia and Cheu 2012; Shen et al. 2009). This approach provides a common framework through which transport and other related sectors can be incorporated and modeled. As mentioned earlier, this methodology involves thinking of all concepts in the real system as continuous quantities interconnected in loops of information feedback and circular causality. Some of the benefits include:

1) A structured framework through which large scale systems can be modeled, analyzed, and tested;
2) The integration of feedback structures instead of the traditional step-by-step/input-output model;
3) The use of available data; and
4) Tracing of the short-term and long-term behavior of a system.

This latter point not only provides insight into the nature of the problem but also allows for timely adjustments to be made. The data needs for a SDM are distinct from those of other simulation approaches. Mayo and Wichmann (2003) identify three key ways data is incorporated in SDM:

1) To provide an initial state from which the simulation begins;
2) To represent any exogenous variables; and
3) To calibrate the model and validate its outputs.
In addition, System Dynamics provides a rich, common media for communication and understanding between the various parties that have an interest in the transportation system. There are, of course, limitations to this modeling approach. Some of these could be looked upon in a general context, while others are specific to the modeling of transportation systems (Abbas and Bell 1994). In general, modeling involves assumptions about behavior in the real world, and this cannot represent reality in a complete fashion, but it can attempt to approach reality. The tendency to include a clutter of causal relations that are irrelevant and the time and spatial dimension of the approach (i.e., spatial aspects and distribution effects are not easily accounted for) are other limitations found in the literature.

The need to incorporate dynamic relationships between transportation and other systems calls for further exploration of the suitability and appropriateness of system dynamics to transportation modeling. Abbas and Bell (1994) establish that this analytical approach is an effective aid in identifying and appraising alternatives to change policy for a future course. System Dynamics may illustrate trade-offs, but it cannot determine what a desirable scenario is, given that decision makers make their own value judgments. Therefore, System Dynamics models are to be used for gaining understanding and for policy analysis, rather than for prediction, which is indeed the case of modeling approaches. They argue that transport investments should be planned not only within the regional and national transport systems, but also within the wider context of the goals and objectives of overall national and regional economic development and for the evaluation of both the short- and the long-term impacts of transportation policies. Hence, the need to understand the potential outcomes of policy decisions, given the fact that transportation investments are very expensive and relatively infrequent. In addition to the fact that the land use responses to transportation investment and policies are often long ranged and difficult to connect causality to transportation investment. The value provided in this context by a System Dynamics approach is precisely the examination under a much wider context.

3.3.2 System Dynamics Models for Land Use and Transportation

Theories in land use and transport interaction identify as expected impacts key factors such as urban density, employment density, neighborhood design, location, city size, accessibility, travel cost and travel time. Figure 3.1 attempts to summarize the impact of urban form on activity and travel (Badoe and Miller 2000). In this figure, activity/travel behavior is shown as the outcome of a complex set of interactions among the various factors mentioned above. In this model, "urban form"
or "land use" (represented by residential density, neighborhood design, and employment density) provides a context of human behavior, which includes location decisions, auto ownership decisions, and ultimately activity/travel decisions.

![Figure 3.1 Interaction between urban form and activity and travel](image)

In order to apply this approach, the remaining of this thesis will divide the work in three steps: preliminary, specified, and comprehensive analysis. The preliminary analysis consists of understanding the system and identifying feedback structures. In the specified analysis, the system structure is constructed and coefficients and equations are specified to conduct a simulation process. Finally, in the comprehensive analysis, the simulation results from different scenarios are estimated and compared, aided by sensitivity analysis, and relevant conclusions and policy suggestions are summarized.
Figure 3.2 Flowchart of System Dynamics Modeling

1. Problem Identification
2. System Boundary
3. Cause-Effect Analysis
4. System Structure
5. Quantitative Analysis Model
6. Simulation
7. Comparison & Evaluation
8. Policy Suggestion

PRELIMINARY ANALYSIS

SPECIFIED ANALYSIS

COMPREHENSIVE ANALYSIS

Kendall Square is a neighborhood in Cambridge, Massachusetts, located at the intersection of Main Street, Broadway, Wadsworth Street, and Third Street; immediately to the east of one of the entrances to the Kendall/MIT subway station. The square is also referred to as the broad business district that is east of Portland Street, northwest of the Charles River, north of the Massachusetts Institute of Technology (MIT), and south of Binney Street.

Since the late 1700's, the Kendall Square has been an important transportation hub, particularly since the construction of the West Boston Bridge, which was replaced with the Longfellow Bridge in 1907. In the nineteenth century, the area was a major industrial center and by the twentieth century was home to distilleries, electric power plants, and factories. When the Longfellow Bridge was constructed, it included provisions for a future rapid-transit subway link to Harvard Square and Boston (now the Red Line). In 1911, the original Kendall subway station was opened and by 1915, MIT moved its campus to Cambridge. Between the 1990s and 2000s, Kendall Square was becoming the site of major cultural shift, associated to the technological revolution of the 1990s. During that time, the area between the square and the Cambridge Side Galleria transformed from an industrial area into a collection of offices and research buildings, housing over 150 biotechnology and information technology firms as of 2011.

4.1. Transit Infrastructure: the Red Line

The last of the four original Boston subway lines, the Red Line is a rapid transit line operated by the Massachusetts Bay Transportation Authority (MBTA) running roughly north-south through Boston into neighboring communities, including Cambridge. The line begins at Alewife station in Cambridge, passes through downtown Boston, with transfers to the Green Line at Park Street, the Orange Line at Downtown Crossing, and the Silver Line at South Station. It later splits at the JFK/UMass station, with branches to Braintree and Ashmont; it further connects to Mattapan via the Ashmont-Mattapan Line.

The line was built in five stages over a period of almost 75 years. The first section built between 1909 and 1912 had four stations, three in Cambridge (Harvard Square, Central Square, and the Kendall/MIT station), plus Park Street station in Downtown Boston. The second stage was built between 1912 and 1918 and was known as the Dorchester Tunnel, which added four stations to the route, two in Downtown Boston (Washington Street and South Station) and two in South Boston.
(Broadway and Andrew Station). A further addition built between 1924 and 1928, known as the Dorchester Extension, was the first to reuse a former railroad right-of-way and added five more stations which connected to Fields Corner (Columbia, Savin Hill, Fields Corner, Shawmut, and Ashmont station). Additional extensions were made in 1966 with the South Shore Extension, a project that added five new stations, four in Quincy (North Quincy, Wollaston, Quincy Center, Quincy Adams) and one in Braintree. The final addition, the Northwest Extension, which started in 1979, added three new stations, two in Cambridge (Alewife and Davis Square) and one in Somerville (Porter Square), but required the relocation of the original Harvard terminal. Plans for this final extension started in the 1930s with proposed alignments that excluded stops at Porter and Davis Square. However, resistance from Cambridge and advocacy from Somerville residents resulted in the inclusion of those two squares in the final route alignment.

4.2. General Trends in Cambridge

This section aims at analyzing general demographic, socio-economic, and economic trends that have been observed in the past two decades in the City of Cambridge. This analysis will allow for the identification of possible relationships between variables and parameters and system boundaries, which will be used in subsequent chapters to develop a system dynamics model for the Kendall Square area.

4.2.1 Population and Socio-economic Characteristics

Based on the US Census Bureau (1990, 2000, 2010) and a report from the Cambridge Community Development Department (2011), the total population in Cambridge has constantly increased from 1990 through 2010, as well as the number of household and residential units. From 1990 to 2000, the population growth in the city is about 5.5 percent and from 2000-2010, of about 3.6 percent. Contrary to conventional wisdom based on assumed correlation between income and auto ownership, mean household income has increased during the last 20 years, while auto ownership in the area has decreased in the last decade from 0.98 to 0.92.
Table 4.1 General Socio-Economic characteristics for the City of Cambridge

<table>
<thead>
<tr>
<th>YEAR</th>
<th>TOTAL POPULATION</th>
<th>HOUSEHOLD POPULATION</th>
<th>POPULATION PER ACRE</th>
<th>MEAN HOUSEHOLD INCOME</th>
<th>VEHICLES PER HOUSEHOLD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>95,802</td>
<td>81,769</td>
<td>23</td>
<td>$55,350</td>
<td>0.96</td>
</tr>
<tr>
<td>2000</td>
<td>101,355</td>
<td>86,692</td>
<td>25</td>
<td>$61,763</td>
<td>0.98</td>
</tr>
<tr>
<td>2010</td>
<td>105,162</td>
<td>88,060</td>
<td>26</td>
<td>$67,297</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Though population has constantly increased during the analysis period, the highest population density has been concentrated around Harvard and Central Square stations with some pockets in the north-east portion of the city (boundary with Somerville).
Figure 4.2 Cambridge Population Density (1990)

Figure 4.3 Cambridge Population Density (2000)
4.2.2 Housing Stock

As a general trend in Cambridge, housing units have increased from around 41,000 units to close to 47,300 units, with an average of 12 units per acre in 2010. The growth in housing density had been 6.1 percent (1990-2000) and 5.4 percent (2000-2010) for the entire city of Cambridge. As of 2010, there were 49,530\(^2\) housing units, from which 35.2 percent of the housing stock were condominiums with 51 or more units, followed by 14.3 percent of two-housing family units.

Table 4.2 Housing Stock at Cambridge

<table>
<thead>
<tr>
<th>YEAR</th>
<th>HOUSING UNITS</th>
<th>HOUSING UNITS PER ACRE</th>
<th>HOUSING PRICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>41,979</td>
<td>10</td>
<td>N/A</td>
</tr>
<tr>
<td>2000</td>
<td>44,725</td>
<td>11</td>
<td>$302,500</td>
</tr>
<tr>
<td>2010</td>
<td>47,291</td>
<td>12</td>
<td>$424,000</td>
</tr>
</tbody>
</table>

\(^2\) According to the Cambridge Community Development Department, the U.S. Census and the Cambridge Assessing Department use different methods for evaluating the size of the housing stock and to determine the owner and renter occupancy rates. Thus, this figure is not strictly comparable to those stated in other tables.
Similar to the patterns observed for the population density in the area, most of the increase in residential density is observed in the Central Square area and along the northeast portion of the city which coincides with Somerville’s city boundary.

Figure 4.5 Residential Density in Cambridge, 1990

Figure 4.6 Residential Density in Cambridge, 2010
4.2.3 Employment

According to the City of Cambridge (2011), there has been a continuous increase in the number of workers in the area, as well as the number of residents working in the area. In 2000, the highest number of jobs was reported, with a total of 115,625. In addition, approximately 23 percent of the residents reported Cambridge as their location of work.

From the figure below (Figure 4.7 through 4.9), by 2010, a great number of firms have been clustering three of the transit stations in the area (Harvard, Central and Kendall Square). Particularly, one can observe that by 2000, most of the area around Kendall Square experienced an increase in employment density. Both Harvard University and MIT are two of the biggest job generators in the area with 17,868 and 8,500\(^3\) jobs, respectively, reported by 2010 (ESRI Business Analyst 2011).

![Figure 4.7 Cambridge Employment Density, 1990 (Source: CTPP 1990)](image)

\(^3\) From the data, it is not clear if these figures include students enrolled at Harvard University and MIT.
Figure 4.8 Cambridge Employment Density, 2000 (Source: CTPP2000)

Figure 4.9 Cambridge Employment Density, 2010 (Source: Murga 2013)
In Table 4.3, figures for residential labor force, number jobs, and number of residents actually working in Cambridge are presented. Though there seems to be discrepancy between the number of jobs reported in the Cambridge area and the number of people who reported Cambridge as their working location there has been an increase in the number of employees; between 1990 and 2010 the number of people working in Cambridge increased by almost 7.2%. In addition to that increase, there has also been an increase in the number of residents who work in Cambridge.

Table 4.3 Residential Working Force in Cambridge

<table>
<thead>
<tr>
<th>YEAR</th>
<th>RESIDENTIAL LABOR FORCE</th>
<th>JOBS REPORTED IN CAMBRIDGE</th>
<th>PEOPLE WORKING IN CAMBRIDGE</th>
<th>RESIDENTS WORKING IN CAMBRIDGE</th>
<th>% OF CAMBRIDGE WORKING FORCE LIVING IN CAMBRIDGE</th>
<th>% OF CAMBRIDGE WORKING FORCE LIVING OUTSIDE CAMBRIDGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>57,151</td>
<td>103,277</td>
<td>109,490</td>
<td>25,730</td>
<td>23.5%</td>
<td>76.5%</td>
</tr>
<tr>
<td>2000</td>
<td>59,965</td>
<td>115,625</td>
<td>114,133</td>
<td>25,554</td>
<td>22.4%</td>
<td>77.6%</td>
</tr>
<tr>
<td>2010</td>
<td>66,062</td>
<td>106,405</td>
<td>117,991</td>
<td>27,774</td>
<td>23.5%</td>
<td>76.6%</td>
</tr>
</tbody>
</table>

4.2.4 Transit Ridership

In this section, trends for transit ridership along the Red Line are documented. Harvard Square has consistently been the station with the highest level of ridership in Cambridge, though transit ridership has continuously increased in all station from 1990 to 2009, except in Porter Square which slightly decreased from 2000 to 2009. From 1990 to 2000, the highest (percentage) increase...
in ridership was observed in Davis, while the lowest change was observed in Kendall/MIT. However, between 2000 and 2009, Kendall/MIT had the highest percentage increase in transit use.

![Graph showing transit ridership along the Red Line](image1)

**Figure 4.11 Transit Ridership along the Red Line**

![Graph showing percent change in transit ridership](image2)

**Figure 4.12 Percent Change in Transit Ridership**
4.2.5 Commuting Patterns TO and FROM Cambridge

According to the CTPP 2000, 40.3 percent of the work trips done by Cambridge residents were done by auto (combining auto and car pool trips). However, the share of residents who commute by auto decreased by 2006-2008 to 35.3 percent (ACS, 2010). At the same time, the share of transit use increased from 24.8 to 28.1 percent between 2000 and 2006-2008. In addition, there was an increase in the share of non-motorized (biking and walking) trips. A report from the city of Cambridge (Cambridge Community Development Department, 2011) also indicates that from those residents who drive to work, 70.8 percent of the trips are done to other towns and states, while 29 percent are done to abutting towns4. Furthermore, for those residents who work in abutting towns, most of the trips were by transit (55.1 percent), representing the highest share of transit use amongst residents, while 42.5 percent of the residents working in Cambridge walk to work.

Table 4.4 Commuting Patterns from Residents and Workers End (CTPP 2000, ACS 2006-2008)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Percent</td>
<td>Number</td>
<td>Percent</td>
</tr>
<tr>
<td></td>
<td>At Place of Residence</td>
<td>At Place of Work</td>
<td>At Place of Residence</td>
<td>At Place of Work</td>
</tr>
<tr>
<td>Total Workers</td>
<td>54,960</td>
<td>100%</td>
<td>56,912</td>
<td>100%</td>
</tr>
<tr>
<td>Drove alone</td>
<td>19,240</td>
<td>35.0%</td>
<td>17,461</td>
<td>30.7%</td>
</tr>
<tr>
<td>Carpool</td>
<td>2,940</td>
<td>5.3%</td>
<td>2,630</td>
<td>4.6%</td>
</tr>
<tr>
<td>Public Transportation</td>
<td>13,625</td>
<td>24.8%</td>
<td>15,973</td>
<td>28.1%</td>
</tr>
<tr>
<td>Walk/Bike</td>
<td>15,555</td>
<td>28.3%</td>
<td>16,770</td>
<td>29.5%</td>
</tr>
<tr>
<td>Other Means</td>
<td>700</td>
<td>1.3%</td>
<td>614</td>
<td>1.1%</td>
</tr>
<tr>
<td>Worked at Home</td>
<td>2,900</td>
<td>5.3%</td>
<td>3,464</td>
<td>6.1%</td>
</tr>
</tbody>
</table>

4 Abutting towns include Arlington, Belmont, Boston, Brookline, Somerville, and Watertown.
Figure 4.13 Cambridge Mode Share at Place of Residence

Figure 4.14 Cambridge Mode Share at Place of Work
Table 4.5 Cambridge Residents Means of Commute to Work (2000-2008) (Source: Cambridge Community Development Department 2011)

<table>
<thead>
<tr>
<th>MEANS OF COMMUTE</th>
<th>(2006-2008) CAMBRIDGE RESIDENTS WHO WORK IN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CAMBRIDGE</td>
</tr>
<tr>
<td>DRIVE ALONE</td>
<td>16.3%</td>
</tr>
<tr>
<td>CAR/POOL</td>
<td>3.5%</td>
</tr>
<tr>
<td>PUBLIC TRANSIT</td>
<td>15.3%</td>
</tr>
<tr>
<td>BIKE</td>
<td>7.6%</td>
</tr>
<tr>
<td>WALK</td>
<td>42.5%</td>
</tr>
<tr>
<td>WORKED AT HOME</td>
<td>13.7%</td>
</tr>
<tr>
<td>OTHER</td>
<td>1.0%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>100%</td>
</tr>
</tbody>
</table>

Figure 4.15 Cambridge Residents Means to Commute to Work (2006-2008)

For those who reported Cambridge as their place of work, the share of auto trips decreased by 10.9 percent (from 58.8 to 53 percent) between 2000 and 2006-2008, while transit and biking trips increased in the same period. For those who work and live in Cambridge, most of the trips are done by foot (42.9 percent), while 16.4 percent drive to work and only 15.5 percent take transit. Public transit share is the highest amongst those workers coming from abutting towns (41.9 percent).
Table 4.6 People Who Work in Cambridge Means of Commute to Work (2000-2008) (Source: Cambridge Community Development Department 2011)

<table>
<thead>
<tr>
<th>MEANS OF COMMUTE</th>
<th>(2006-2008) PEOPLE COMMUTING TO WORK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FROM CAMBRIDGE</td>
</tr>
<tr>
<td>DRIVE ALONE</td>
<td>16.4%</td>
</tr>
<tr>
<td>CAR/POOL</td>
<td>3.6%</td>
</tr>
<tr>
<td>PUBLIC TRANSIT</td>
<td>15.5%</td>
</tr>
<tr>
<td>BIKE</td>
<td>7.7%</td>
</tr>
<tr>
<td>WALK</td>
<td>42.9%</td>
</tr>
<tr>
<td>WORKED AT HOME</td>
<td>13.8%</td>
</tr>
<tr>
<td>OTHER</td>
<td>0.2%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>100%</td>
</tr>
</tbody>
</table>

Figure 4.16 People Working in Cambridge Means to Commute to Work (2006-2008)

4.2.6 Car Ownership

Nearly 30 percent of the households have no vehicles and 50.3 percent own at least 1 vehicle between 1990 and 2010. The average number of vehicles per household in 1990, 2000, and 2010 was 0.96, 0.98, and 0.92 respectively. This trend is shaped by a growing number of households who choose not to have an automobile. It can be expected that an increase in auto ownership, reduces the total transit trips in the area. However, as observed in the transit section, ridership constantly increased in most stations.
4.2.7 Land Use

Most of the land is dedicated to multi-family residential all through Cambridge, with industrial and institutional lots around the southern portion of the city mostly around Kendall/MIT, as it can be observed through Figures 4.18-4.20. In addition, one can observe a strip of commercial land use following the MBTA Red Line alignment.
Figure 4.19 Land Use (1999)
Figure 4.20 Land Use (2005)
By 2005, there was a larger mix of commercial and residential land use along the MBTA alignment, as well as a decrease in the share of industrial land particularly around MIT; residential land accounted for 33 percent, while commercial and industrial land covered 9% of the land (Figure 4.21).

![Land Use 2005](image)

**Figure 4.21 Percentage of Land Use Purposes, 2005**

### 4.3. Kendall Square: A Closer Look

Kendall Square offers a unique combination of accessibility to people and other opportunities which have encouraged employment and population changes. Currently, the area also known as Technology Square has become a hub for technology start-ups. These start-ups and high-tech firms are lured to the area as a result of its proximity to MIT and, as mentioned earlier, by 2011 the area provides office space for more than 150 bio-technology and information technology firms.

MIT owns some of the commercial real estate in the Square and has been actively building space for new high-tech tenants as well as rebuilding their own facilities, such as the Stata Center and the MIT Sloan School of Management. In addition, a number of high-level office complex parks can be found in the area, including the One Kendall Square, the Technology Square, the Cambridge Center office development, and the Cambridge Innovation Center\(^5\). Employment

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\(^5\) The Cambridge Innovation Center is a shared office space for start-ups and venture capital firms currently occupied by almost four hundred businesses from one person size up.
According to the Census Data for 1990, 2000, and 2010, general trends for the Kendall Square area have been increasing, with a percentage increase in the total population from 1990 to 2010 by of 17.2.

Table 4.7 General Characteristics for Kendall Square (1990 - 2010)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1990</th>
<th>2000</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>12,655</td>
<td>13,965</td>
<td>15,282</td>
</tr>
<tr>
<td>Households</td>
<td>3,922</td>
<td>4,446</td>
<td>5,511</td>
</tr>
<tr>
<td>Workers</td>
<td>7,008</td>
<td>8,128</td>
<td>8,605</td>
</tr>
<tr>
<td>Jobs</td>
<td>36,383</td>
<td>37,476</td>
<td>48,803</td>
</tr>
</tbody>
</table>

4.3.1 Employment

As can be observed in Table 4.7 employment increased during 1990 to 2010 by 25.4 percent between 1990 and 2010. According to Peralta-Quirós (2013), who has analyzed in detailed Kendall Square and other employment centers in the Greater Boston Area between 1990 and 2000, Kendall Square has experienced one of the highest job growths in the metropolitan area, in line with the Central Business District (CBD), the Longwood Medical Center, and Logan Airport. In addition, she finds that Kendall Square does appear to have the highest job increase in this time period, comparable only to the CBD, which historically has been a major employment center.

The analysis further suggests that the area further encourages the concentration of certain types of industries, particularly those pertaining to scientific and educational industries, which are complementary, but yet competing industries. In addition, she points out that Kendall is able to offer a unique combination of research facilities and education centers (provided by MIT) of great value to the scientific industries. Hence, although Kendall does not compete with other strong employment centers such as the CBD (a financial cluster), it is able to offer a unique work and educational environment only found in the area. Kendall Square provides a type of environment which becomes attractive to other companies in these industries, since it allows a collaborative and innovative climate.
The following table (4.8) presents a list of existing firms and an estimate of the number of employees.
### Table 4.8 Kendall Square top employers and average number of employees

<table>
<thead>
<tr>
<th>COMPANY NAME</th>
<th>EMPLOYEES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akamai Technologies</td>
<td>700</td>
</tr>
<tr>
<td>Alnylam Pharmaceuticals Inc.</td>
<td>170</td>
</tr>
<tr>
<td>Amazon.com</td>
<td>N/A</td>
</tr>
<tr>
<td>American Red Cross</td>
<td>100</td>
</tr>
<tr>
<td>Amgen Inc</td>
<td>9</td>
</tr>
<tr>
<td>AT&amp;T</td>
<td>N/A</td>
</tr>
<tr>
<td>Art Technology Group</td>
<td>300</td>
</tr>
<tr>
<td>Biogen Idec Inc.</td>
<td>15</td>
</tr>
<tr>
<td>Broad Institute</td>
<td>400</td>
</tr>
<tr>
<td>Cambridge Innovation Center</td>
<td>20</td>
</tr>
<tr>
<td>Cambridge Police Department</td>
<td>300</td>
</tr>
<tr>
<td>Camp, Dresser &amp; McKee (CDM)</td>
<td>600</td>
</tr>
<tr>
<td>Cell Press Editorial</td>
<td>100</td>
</tr>
<tr>
<td>Computer Sciences Corporation</td>
<td>200</td>
</tr>
<tr>
<td>Corden Pharma</td>
<td>100</td>
</tr>
<tr>
<td>Draper Laboratory</td>
<td>1000</td>
</tr>
<tr>
<td>Endeca Technologies Inc.</td>
<td>35</td>
</tr>
<tr>
<td>Entersystems Corporation</td>
<td>300</td>
</tr>
<tr>
<td>Forrester Research</td>
<td>442</td>
</tr>
<tr>
<td>Genzyme Corporation</td>
<td>1000</td>
</tr>
<tr>
<td>Google</td>
<td>3</td>
</tr>
<tr>
<td>Inter Systems Corporation</td>
<td>140</td>
</tr>
<tr>
<td>Marriott Hotel</td>
<td>530</td>
</tr>
<tr>
<td>Massachusetts Institute of Technology</td>
<td>9200</td>
</tr>
<tr>
<td>Microsoft Corp.</td>
<td>15</td>
</tr>
<tr>
<td>Millennium Pharmaceuticals</td>
<td>9</td>
</tr>
<tr>
<td>NEPC</td>
<td>150</td>
</tr>
<tr>
<td>Pegasystems</td>
<td>200</td>
</tr>
<tr>
<td>R R Donnelley</td>
<td>120</td>
</tr>
<tr>
<td>Residence Inn</td>
<td>100</td>
</tr>
<tr>
<td>SAP Labs</td>
<td>100</td>
</tr>
<tr>
<td>Senior Whole Health LLC</td>
<td>184</td>
</tr>
<tr>
<td>Shire Human Genetic Therapies</td>
<td>276</td>
</tr>
<tr>
<td>Unisys Corporation</td>
<td>500</td>
</tr>
<tr>
<td>US Department of Transportation</td>
<td>500</td>
</tr>
</tbody>
</table>
4.3.2 Residential Location

Similar to the report conducted by the City of Cambridge (2011) (Table 4.5), Peralta-Quirós (2013) indicates that most of the home based work trips destined to the Kendall Square area are originated in the Square or in the vicinity of Cambridge. Given that Kendall Square houses MIT and its students, it is not surprising that a large part of the people that are employed there might also live on campus. In addition, new housing developments in the area, as well as in Main Street and Central Square, might provide residences to many of the workers in the area.

<table>
<thead>
<tr>
<th>Company</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex Pharmaceuticals</td>
<td>1000</td>
</tr>
<tr>
<td>Via Cord LLC</td>
<td>110</td>
</tr>
<tr>
<td>Whitehead Institute</td>
<td>500</td>
</tr>
<tr>
<td>World Wide Web Consortium</td>
<td>15</td>
</tr>
<tr>
<td>Yahoo</td>
<td>N/A</td>
</tr>
</tbody>
</table>

4.3.3 Commuting Patterns

The study by Peralta-Quirós (2013) also looked at commuting patterns in the area, particularly mean travel times for all modes and median trip length for all trips, based on 2000 CTPP data.
According to the analysis, Kendall Square has average commuting times that are amongst the lowest of all employment centers in the Boston Area.

- **Auto Travel Times** - shorter than those to the CBD, with mean travel times of 25.0 to 40 minutes. However, the median travel times are much lower than the average, which suggest that most of the trips made to Kendall are of shorter length.

- **Transit Travel Times** - median travel times to the area suggest that most trips are of a shorter length, though travel times are skewed by longer commuter rail trips. Compared to auto trips, the area seems to be more accessible by transit, as travel times are shorter than those by auto.

![Figure 4.25 Mean travel times for made trips by auto, displayed by trip destination (Source: Peralta-Quirós 2013)](image)

---

6 Since not all blocks are transit accessible, the information is scattered. In addition, the data includes trips made by commuter rail and thus might increase the average and mean travel times made by transit trips.
The analysis concludes that, by 2000, Kendall Square has a better access for people who were making the commute by transit. The data further suggests that commuters live close to Kendall or in close proximity to transit lines, as travel times by transit were lower than those by car.

### 4.3.4 Modal Split

The 1990 CTPP and 2000 CTPP data suggests that there is a stronger reliance on public transportation at the Kendall Square. As Peralta-Quirós (2013) points out, by 1990, the CBD was the only region where the auto did not serve the majority of the trips. However, by 2000, a number of employment areas, including Kendall Square, increased the share of trips served by other means other than auto. In recent years, there has been a shift away from auto to walk, transit, and bike, though rail remains to be the most common form of transit. Table 4.9 illustrates the changes in modal split for the Kendall Square residents and for workers in the area. As mentioned, the share of driving trips has decreased from 47.6 percent to 33.6 percent in the last 20 years for the residents, while for the workers it has decreased from 67.4 percent to 59.9 percent. The highest percent change in mode share from the destination side (workers end) is observed with transit trips which increased by 26.2 percent, suggesting that there is a higher correlation between work trips and job location. As in the case of the general trends observed in Cambridge, the highest percent change in
mode share for the residents is observed with biking and walking trips which increased about 33.3 percent between 1990 and 2010.

Table 4.9 Kendall Square Modal Split at Place of Residence and at Place of Work (1990 - 2010)

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At Place of Residence</td>
<td></td>
<td>At Place of Work</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Workers</td>
<td>17,480</td>
<td>100%</td>
<td>18,225</td>
<td>100%</td>
<td>22,101</td>
<td>100%</td>
<td>46,094</td>
<td>100%</td>
<td>47,014</td>
<td>100%</td>
</tr>
<tr>
<td>Drove alone</td>
<td>6,265</td>
<td>35.8%</td>
<td>6,115</td>
<td>33.6%</td>
<td>5,992</td>
<td>27.1%</td>
<td>26,439</td>
<td>57.4%</td>
<td>25,345</td>
<td>53.9%</td>
</tr>
<tr>
<td>Carpool</td>
<td>1,269</td>
<td>7.3%</td>
<td>787</td>
<td>4.3%</td>
<td>1,051</td>
<td>4.8%</td>
<td>4,612</td>
<td>10.0%</td>
<td>3,703</td>
<td>7.9%</td>
</tr>
<tr>
<td>Public Transportation</td>
<td>4,839</td>
<td>27.7%</td>
<td>5,173</td>
<td>28.4%</td>
<td>6,575</td>
<td>29.7%</td>
<td>9,584</td>
<td>20.8%</td>
<td>12,431</td>
<td>26.4%</td>
</tr>
<tr>
<td>Walk/Bike</td>
<td>5,107</td>
<td>29.2%</td>
<td>6,150</td>
<td>33.7%</td>
<td>8,483</td>
<td>38.4%</td>
<td>5,459</td>
<td>11.8%</td>
<td>5,035</td>
<td>10.7%</td>
</tr>
</tbody>
</table>

As mentioned in Chapter 3, there are limits to growth in areas solely served by auto (Pushkarev and Zupan 1977). As seen in Table 4.9, most of the work trips to the Kendall area are done by car (67.4 and 59.9 percent for 1990 and 2000 respectively), but the area has experienced an increase in the number of jobs during that same time, which may only be attributed to the accessibility obtained by public transportation and non-motorized modes, as workers are choosing to live in close proximity to their job location.

Figures 4.27 through 4.31 illustrate the changes in modal split at the around the Kendall Square area from 1990 to 2010 for both the residents and workers end. A common trend for the last 20 years for the area is a move towards more sustainable commuting modes (Murga, 2013). If we were to consider that the number of residential working trips has increased from 17,480 to 22,101 (a 20.9 percent increase), there are 491 less trips by auto, 1,736 more trips by transit, and 3,376 more trips either by walking or biking. From the workers end, the graphs illustrate a higher reliance on the automobile.
Figure 4.27 CTPP 1990 Modal Split at the Residence Side

Figure 4.28 CTPP 2000 Modal Split at Residence Side
Figure 4.29 ACS 2010 Modal Split at Residence Side

Figure 4.30 CTPP 1990 Modal Split at the Work Side
During the past decades Kendall Square has continued to experience an increase in jobs, particularly highly skilled jobs. The proximity of the Square to MIT and the cluster of educational and scientific industries, has contributed to the unique culture and identity of Kendall Square Area. As Peralta-Quirós writes: "Kendall Square does not compete to provide the best financial services, but rather defined its own niche, by combining the complementary activity of research and academic ventures, with scientific and technology companies" (2013).
5. Preliminary Analysis: A System Dynamics Model for Kendall Square

This chapter is intended to present and describe the conceptual model developed for Kendall Square. In a preliminary analysis, the understanding of the system characteristics deepens, the boundary of the system is defined, while the internal and external variables are identified, especially the feedback causal loops of the variables. The purpose of the model is to discern the different effects of key variables on transit ridership and also to explain the relationship among these variables.

The model is built using Vensim (Ventana System, Inc 2013), a simulation environment which allows an integrated framework for conceptualizing, building, simulating, analyzing, optimizing and deploying models of complex dynamic systems.

5.1. Problem Identification

To identify the problem we need to raise the following question: Did the development of Kendall Square happen by chance? Is the Red Line the main catalyst for its current conditions? Did the transportation investment, coupled with proximity to MIT, availability of space for development, parking policies, changes in mobility patterns, amongst other policy measures influenced its success? Obviously, these questions should shape the model in order to provide an appropriate answer.

As presented in chapter four, Kendall Square has grown to be a major employment center, particularly for pharmaceuticals, biotech companies, and innovation and technology research. The area has attracted numerous companies due to the unique environment and transit, auto and non-motorized accessibility. Given its proximity to the Massachusetts Institute of Technology (MIT), this allows access to a pool of potential, knowledge-based skilled workforce who bring in the latest technology and research available. All these factors will be taken into consideration in order to build the model structures.

5.2. System Boundaries

The model built for Kendall Square takes into consideration changes within approximately a half-mile radius of the MBTA Red Line station and a time span from 1990 to 2040. The model consists of
population, employment, housing, and transportation, specifically the availability of parking and the MBTA Red Line service. The model is essentially a two-zone model: the Kendall Square area and the outside world.

5.3. Influencing Factors and Causal Loop Diagrams

The overall model system consists of four major sub-models: the population sub-model, the employment sub-model, the land-use sub-model, and the transportation sub-model. Figure 5.1 shows the relationships among these sub-models.

- All else being equal, a plus sign (+) over an arrow from X to Y implies that if X increases so does Y, or if X decreases Y also decreases. A minus sign (-) indicates the reverse effect. The (+) sign indicates only that changes are reinforced – it does not mean that the effects are necessarily good. The (-) sign indicates only that changes are resisted – it does not mean that the effects are necessarily bad.
- The double line on the arrow represents a delay in the system – a transition that requires substantially more time to occur that the transition between other variables connected by a causal arrow. Naturally, delays occur in all systems; it may be of the order of seconds, minutes, hours, months, years, etc.
- Dashed lines represent weak relationships.

It should be noted that the following sub-models were developed independently and are based on various models found in the literature, though it incorporates relationships and variables that are specific to this thesis. There are several causal relationships that are omitted for simplicity though they are taken into consideration in other sub-models so that all are linked when the model is compiled.
Figure 5.1 Relationship among sub-models

A description of each of these sub-models follows:

- **Employment (Economy) – Population – Travel Demand – Congestion – Employment (Economy) (B1):** Economic development attracts more in-migration population. This increase in population generates more travel demand which in turn increases congestion. Serious congestion results in a decrease in economic development. This corresponds therefore to a balancing loop.

- **Population – Housing Development – Migration (R1):** All else equal, the increase of population and households encourage more housing developments. Potentially, it improves housing market conditions and induces more in-migration. This represents instead a reinforcing loop.

- **Population – Travel Demand – Congestion – Migration (B2):** Increase in population causes more households, more travel demand, and more congestion. Congestion, on the other hand has a negative effect on net migration (serious congestions problems discourages the motivation of potential migrants), and dampens population increases.

- **Housing Development – Land Availability (B3):** Housing development is encouraged by population growth. However, as housing development progresses, the remaining available land decreases, as total available land is fixed. Therefore, housing developments are controlled by land availability constraints.
- Employment (Economy) – Land Availability (B4): Similarly to housing development, employment growth is constrained by land availability.

- Congestion – Transport Supply (B5): On the one hand, increases in transportation capacity through infrastructure (lane-miles or transit lines) lessens congestion (positive effect), at least in general. On the other hand, serious congestion puts pressure in favor of the development of new infrastructure (negative effect).

5.3.1 Population and Housing Development

This section outlines the relationship between population and housing. In general, when the urban population increases housing shortage increases. Housing shortage and availability of land for additional housing can drive construction of new housing. Addition of new housing, increases the housing supply rate in the city, and thus in turn, increases the attractiveness of the area, causing an inflow of people to the city. The concept of the attractiveness of a city as a factor influencing population inflow is based on Alfeld and Graham's model (Alfeld and Graham 1976).

The relationship between population and housing consists of six loops as shown in Figure 5.2, including two positive (or reinforcing) feedback loops (R1-R2) and four negative (or balancing) feedback loops (B1-B4). An increase in population, as a result of an inflow of population, is accompanied by an increase in housing demand. As the demand for housing increases, rent prices increase, increasing the attractiveness of housing development in the area. As new houses are developed, the stock of housing units' increases; further increasing the attractiveness of the area.

The increase in the area's attractiveness, of course, leads to further increase in urban population inflow; the higher population consumes part of the housing stock, which in turn decreases the area attractiveness, as expressed by the balancing loop B4.
As mentioned, the attractiveness for a developer to develop in a given zone is ultimately determined by the rent which can be achieved. As shown in balancing loop (B1), rent prices are determined by the demand for housing, which is a function of the number of housing units in the zone. As new houses are developed, the stock of housing units' increases, which in turn reduces the demand for development, reduces the rent achievable, and further reduces the attractiveness to develop.

However, all else being equal, reinforcing loop (R2) shows that as new housing becomes available, the demand for development reduces, which reduces rent and land prices, which in turn makes development more attractive.

Loops (B2) and (B3) present the restriction of available land and its effect on land prices. As new housing units are being introduced, the available land for development reduces, reducing both the attractiveness for development and the price of the land; the latter further reduces the attractiveness of development.
Balancing loop (B4) shows that when housing supply rate increases, urban attractiveness, population inflow, and urban population also increases. However, when population increases, the housing supply rate decreases, completing the loop.

5.3.2 Employment and Population

In this section, the relationship between employment growth and population is presented. As population grows, the quantity of economic activity in the area also increases. However, if the number of jobs is held constant, employment rate decreases, decreasing the attractiveness of the area and future population growth; through this balancing feedback loop (B5), population is controlled.

New businesses will be attracted to the area as a result of the increase in population and economic growth. This increase in business activity increases the demand for labor represented by the number of jobs available, but is constrained by the availability of land, which controls the inflow of businesses into the city. In addition, the fraction of the working population in the area is not only influenced by an increase in the population, but also by its proximity to MIT, which offers a pool of knowledgeable and skilled, young professionals.

Figure 5.3 CLD Employment and Population Sector
The relationship between economic activity and the population consists of three loops, one reinforcing (R3) and two balancing (B5-B6) loops. Balancing loop (B5) shows that an increase in employment rate is linked with an increase in the attractiveness of the area, which causes an increase in the inflow of population and in the labor force.

The increase in labor force decreases however employment rate, decreasing in turn the area attractiveness. This increase in labor force also increases the inflow of businesses as employees will benefit from agglomeration benefits. When land available for economic development increases, business inflow increase, and hence so too can the business activity. However, an increase in businesses causes a decrease in the available land for economic development; this is represented by balancing loop (B6).

Finally, reinforcing loop (R3) shows that as business inflow increases, there is an increase in the quantity of economic activity, in the number of jobs, and hence in the employment rate. This increase in employment rate makes the area more attractive for people to move in, further increasing the labor force and encouraging an increase in economic activity.

The attractiveness of the area is not only determined by the employment rate, but also is a function of its accessibility to the area, which is explained in the next section. In general, locations with better accessibility to workplaces, retail, education, and leisure facilities will be more attractive for residential, office, and retail developments, will have higher land prices and be developed faster.

### 5.3.3 Travel Demand and Congestion

The relationship between the demand for travel and congestion is presented in this section. In order to lead the discussion, we will first introduce a feedback structure for auto travel demand and its relation with traffic congestion and parking supply. A second structure illustrates the relationship between demand for transit and congestion in the transit network.

The provision of policies leading to higher road capacity and more parking spaces attract usage of automobile, which in turn might lead to the construction of more roads and parking spaces, reinforcing the cyclical process shown in Figure 5.4. Congestion is one of the most prevalent transport problems in large urban agglomerations and is particularly linked with motorization and the prevalence of the automobile, which increases the demand for transportation infrastructure. The increase in auto ownership expands the demand of parking space, as vehicles spend the majority of the time parked, which leads to
space consumption problems particularly in central areas. Congestion and parking are also interrelated since looking for a parking space creates additional delays and impairs local circulation.

This first model of travel demand consists of four balancing loops (B7-B10) and one reinforcing loop (R4). The first balancing loop (B7) shows that as more road expansion projects are introduced, road capacity increases, which in turn reduces travel times as congestion levels (presumably) decrease, thus reducing the pressure to alleviate traffic congestion. However, there is a compensating feedback due to the response to the decreased congestion. Balancing loop (B8) shows that driving becomes more attractive as travel times decrease, which increases the total number of auto trips, resulting in higher traffic volumes and therefore higher travel times. However, as travel times increase, driving becomes less attractive. In addition, balancing loop (B9) shows that as driving becomes more attractive and auto trips to an area increase, the searching time for a parking space increase, therefore, increasing the total travel time.
The desired travel time, coupled with inadequate public transport, increases the attractiveness of driving which in turn decreases transit ridership. The decrease in patronage to public transportation leads to an increase in cars per person, which eventually increases the number of cars in the city, leading to an increase in traffic volumes, which is represented by balancing loop (B10). The delay in reduction of public transportation support arises from two factors: (1) it takes a while for individuals to change their lifestyles and (2) the decision to purchase a vehicle is a function of the socio-economic characteristics of the individual - individuals cannot afford to buy cars when income levels are low. The shift from public transport to personal cars arising from improved income levels is gradual and often goes unnoticed (Armah, Yawson, and Pappoe 2010).

On the other hand, an increase in infrastructure projects translates into an increase in auto accessibility of the area, which increases the inflow of population and economic activity to the area.

As accessibility by car to jobs and people increases, more auto trips are made and traffic volumes continue to increase. As travel times increase, the pressure to reduce congestion fosters infrastructure projects, which increase the capacity of the network, further increasing auto accessibility of the area. This reinforcing feedback is shown by loop (R4). Though the original goal was to reduce traffic congestion, the outcome indicates that the feedback loops often serve to reinforce the problem. Therefore, the whole system is caught in a feedback structure where public transport degrades, traffic increases and, in the end, congestion increases even more.

The second causal loop diagram shows the relationship between transit infrastructure and congestion. The model consists of three reinforcing loops (R5, R6, and R7) and two balancing loop (B11 and B12). Following Hernández's model for ridership in the Basque Country (2011), ridership increases often follow the institutional compromise to expand a system. Reinforcing loop (R5) indicates that as ridership increases, the attractiveness of projects to expand the system increases, resulting in an increase in transit accessibility, which leads to further increases in ridership and encourages future expansions. Similar to the increase in auto accessibility mentioned earlier, the increase in accessibility by transit increases the inflow of population and business activity into the area. As more people and jobs are within reach of the transit system, transit becomes more appealing and ridership continues to increase, as shown by reinforcing loop (R6).

As ridership continues to increase, congestion on the transit network increases. An increase in transit congestion has two effects: a decrease in accessibility by transit as travel times increase - shown by balancing loop (B11) – and an increase in pressure for changes in the network's operations. It should be noted then, that the operators' ability to make these changes is both a
function of the financial capabilities of the agency and of the political will. If conditions are favorable, and after some delay, the network is improved (by higher frequencies, comfort levels, etc.), resulting in an increase in the quality of services. This increase in the quality of services not only increases the attractiveness of public transportation, but also reduces the appeal of driving. This feedback is shown by reinforcing loop (R7). Lastly, a second balancing loop counteracts the growth in ridership due to the limitations of finite resources. Balancing loop (B12) shows that as the operator makes changes to the network (e.g. increases in the frequency of services), the capacity utilization increases, therefore the remaining capacity decreases. As the remaining infrastructure capacity decreases, the attractiveness to the operator for operational changes in that network decreases. However, as the remaining infrastructure capacity is reduced, the attractiveness and pressure for future expansions of the regional network tends to increase.
6. Specified Analysis: Executable Model and Simulation

In this section an executable model is presented, which employs a larger subset of system dynamic modeling techniques, including various stock and flow structures, to describe the four interconnected sub-models that describe the system of the Kendall area. This chapter translates many of the concepts discussed earlier into appropriate variable format (stocks and flows) and functional relationships.

- **Stocks** – represent a part of a system whose value at any given instant in time depends on the systems past behavior; it represents the accumulated volume (or "levels").
- **Flows** – represent the rate at which the stock is changing at any given instant; they either flow into a stock (causing it to increase) or flow out of the stock (causing it to decrease).

The chapter discusses in detail each of the sub-models, including how each relationship has been specified, in terms of endogenous or exogenous variable inputs, the general model assumptions, as well as the description of various scenario alternatives selected for testing.

6.1. System Structure

The model of the Kendall Square area consists of population, business and housing development, travel demand, and transit ridership, showing the impact of each "stock", and the results of their interaction. The input variables for the simulation are adopted from the US Census Bureau (1990, 2000, 2010), the Census Transportation Planning Package (CTPP, 1990, 2000), Cambridge Statistics Report (Cambridge Community Development Department 2011), and other characteristics of the study area.

For presentation purposes, the sub-models are shown independently, though it should be noted that many of these variables are shared across the sub-models and represent the interaction of these sub-systems.
6.1.1 Attractiveness of the Kendall Square Area

The main objective of this thesis is to describe the different dynamics that are observed in the Kendall Square area, in particular those that have made the area so attractive to live and do business. In order to define this attractiveness, the effects of the changes in population, business structure (companies and start-ups), housing development, and accessibility to the area are considered.

- Attractiveness as a place to live is taken to be a function of the availability of three characteristics: suitable housing, employment, and accessibility. Though in reality there are other factors affecting attractiveness (e.g. incomes, rent prices, crime rates, etc.), these were the traits chosen because they are fundamental aspects that people need: somewhere to live and work and the capability to access both.

- For businesses, attractiveness is assumed to be a function of availability of land, the possibility of recruiting a suitable workforce, and the accessibility to customers and employees. While other factors could be also hypothesized, these are considered fundamental for business needs in order to operate: land availability, workforce, and access.

As mentioned in Chapter 5, the proximity to MIT is considered an important attractor and influential factor of the area. In order to estimate the attractiveness for development of the area an Attractiveness Multiplier is estimated, which takes into consideration the accessibility of the area (for residents and for workers), the potential labor force, the housing market, the existence of mixed development, and the proximity to MIT, which in turn will influence the inflow of new comers to the area. Each of these variables is described in subsequent sections.

\[
\text{Attractiveness Multiplier} = \text{Attractiveness of Housing Multiplier} \times \text{Attractiveness of Job Multiplier} \times \text{Area Accessibility} \times \text{MIT Proximity}
\]

For the Kendall Square area, MIT's proximity takes a value of 1.

6.1.2 Population

The population sub-model presented in this section estimates the model target population as that located approximately within a half mile radius of the Kendall Square Station. This simple demographic model aggregates the number of people into a single stock, with birth and death rates
proportional to the population. It further assumes that there is an additional inflow of new comers as a result of the activity of the population and an out-migration. One limitation of this first-order structure is that: those born can immediately reproduce and are just as likely to die as the oldest members of the population. Therefore, when setting the equations and parameters for this model, an additional assumption was made: most of the population within the half mile radius corresponds to young, professionals, most likely being single. This assumption allowed for a reduction of birth and death rates, though still allowing for families and older people to locate in the area.

- **Population** – The population is accumulated on an annual basis in units of people, with an initial value of 12,655 based on the 1990 population within approximately half mile radius of Kendall Square. (Units = People)

  \[ \text{Population} = \text{INTEG}(\text{Births+New Comers-Deaths-Outmigration,Initial Population}) \]

- **Births /Deaths** – The births and deaths are taken as the product of the population at time \( t \) times the birth or death rate. (Units = People/Year)

  \[ \text{Births} = \text{Population} \times \text{Birth Rate} \]
  \[ \text{Deaths} = \text{Population} \times \text{Death Rate} \]

- **Birth Rate** – The average birth rate (per 1,000 population) by 1990 is 0.0005 and is assumed to be constant over the entire period. (Units = 1/Year)

- **Death Rate** – The average birth rate (per 1,000 population) by 1990 is assumed to be 0.0003 and is constant over the entire period. (Units = 1/Year)

- **New Comers** – New comers are defined as the population that is attracted every year to area as a result of the area’s activity and to socioeconomic factors that can influence each population group. Generally, migration reflects the job market condition, housing conditions, and even traffic conditions in the area. It is a function of the attractiveness of the area, the “immigration normal”, and the current population. (Units = People/Year)

  \[ \text{New Comers} = \text{Population} \times \text{Immigration Normal} \times \text{Attractiveness Multiplier} \]

- **Immigration Normal** - Represents the fraction of the population that will migrate to this area. This exogenous variable is assumed to be 0.0045 (Units = 1/Year).

---

\(^7\) Note that stocks are simple “integrals” (INTEG) of the rates flowing in and out, which add to the initial stock value.

\[ \text{STOCK} = \text{INTEG}(\text{INFLOW - OUTFLOW, INITIAL VALUE}) \]
\hspace{1cm}

**Figure 6.1 Population Stock**

- **Outmigration** – The model assumes that a fraction of the population migrates to another city and that it is a function of the current population, the outmigration normal, and the effects of employment and housing. Similar to the inflow of people, the migration of the residents out of Kendall could be a result of the activities in the area. High levels of congestion, housing prices, decreasing labor market, reduction of transit accessibility, amongst others, most likely influence the decision of residents to move somewhere else. However, for simplicity, the model only considers the effect of housing and employment using two table functions\(^8\). For example, as unemployment rates in the area increase (labor force to job ratio higher than 1), more people will leave the area as competition for the existing jobs increases. The effect of housing availability is captured through a lookup function using as an input the houses to household ratio (both ratios are described in later sections). In addition it assumes that housing has a higher effect on migration when compared to jobs. (Units = People/Year)

\(^8\) A table function or lookup function is used to capture nonlinear relationships. The relationship is specified as a table of values for the independent and dependent variable.
Outmigration =
\[ \text{Outmigration Normal} \times \text{Population} \times (0.35 \times \text{Effect of Employment} + 0.65 \times \text{Effect of Housing}) \]

- **Effect of Employment** – Look-up function that takes the ratio of the labor force to job and determines the effect on the decision of people to leave the area. The reasoning behind this variable: if unemployment rates in the area are high (labor force > jobs), then people may decide to relocate somewhere else as competition for the available positions is high.

\[ \text{Effect of Employment} = \]
\[ \text{WITH LOOKUP} (\text{Labor Force to Job Ratio}, ((0,0),(3,3),(0,0.085),(0.49,0.101),(1.06,0.20),(1.43,0.45),(1.53,0.72),(1.61,1.16),(1.72,2.066),(1.86,2.99))) \]

![Figure 6.2 Effect of Employment on decision of residents to move out](image)

- **Effect of Housing** – Look-up function that measures the effect of housing on the decision of people to move out of the area using the houses to household ratio as an input. Understanding that the relationship between housing supply and moving in/out of an area is much more complex, as for example there are differences between movers and renters, the model takes on a very simple approach: if housing is in excess (houses > households), then the effect of moving out decreases as excess housing reduces demand for housing, therefore rent prices fall. The model assumes that most of the people in the area are renters.
Effect of Housing =
WITH LOOKUP (Houses to Household Ratio,([(0,0)-(5,1)],(0,1),(0.2,0.75),
(0.4,0.5),(0.55,0.35),(0.8,0.2),(1,0.1),(1.2,0.05),(2,0.009),(3,0.005),(4,0.001),(5,0))}

- Outmigration Normal – Exogenous variable which represents the fraction of the population that will leave the area and is assumed to be 0.009 annually over the entire period. (Units = 1/Year)

6.1.3 Housing Development

This sub-model aims at determining the number of housing units (stock) in the area. As described in chapter 5, the major factors influencing housing development is the generation of new households and the constraints on land policy. As the population in the area increases, the amount of housing required increases, encouraging the construction of new housing units. However, this construction is constrained by the amount of land available for housing. In addition, as more housing is available (houses to household ratio increases), the area becomes more attractive for people to relocate here (new comers).
The housing stock is determined by the number of housing construction and the housing demolitions. The initial housing stock for Kendall Square is assumed to be 4,266. (Units = House)

\[ \text{Houses} = \text{INTEG} (\text{Housing Construction} - \text{Housing Demolition} - \text{Initial Housing}) \]

- **Houses** – The housing stock is determined by the number of housing construction and the housing demolitions. The initial housing stock for Kendall Square is assumed to be 4,266. (Units = House)

- **Housing Construction** – This variable represents the actual housing units that could be constructed over a time period. The construction of these housing units is a function of the demand for new housing (required housing), a housing construction normal, and a housing multiplier. (Units = House/Year)

\[ \text{Housing Construction} = \max(0, \text{Required Housing} \times \text{Housing Construction Normal} \times \text{Housing Construction Multiplier}) \]

- **Housing Construction Normal** – exogenous variable that determines the rate at which housing construction occurs; it is assumed to be equal to 0.025. (Units = 1/Year).

- **Required Housing** – represents the demand for new housing in the area and is determined by the difference between the current housing stock and the number of housing needed by the population size. (Units = House)
Required Housing = Equilibrium Housing - Houses

- **Equilibrium Housing** – represents the total number of households in the area. It assumes a constant household size of 1.8 people per household. (Units = House)

  \[ \text{Equilibrium Housing} = \frac{\text{Population}}{\text{Household Size}} \]

- **Housing Construction Multiplier** – is a function of the housing land multiplier; this variable estimates a multiplier based on the availability of land. (Units = Dimensionless (Dmnl))

  \[ \text{Housing Construction Multiplier} = \text{Housing Land Multiplier} \]

- **Housing Land Multiplier** – it captures the effect of residential developed land and the remaining available land for residential development through a table function. Though land is consumed as more development occurs in the area, the attractiveness of construction increases as long as there is a demand for housing in the area (see causal diagram in Chapter 5). However, as land becomes scarce, land prices increase and the attractiveness of the area decreases. (Units = Dmnl)

  \[ \text{Housing Land Multiplier} = \text{WITH LOOKUP (House Land Fraction Occupied,[(0,-0.03)\rightarrow(1.4,2)],(0,0.4),(0.1,0.7), (0.2,1),(0.3,1.25),(0.4,1.45),(0.5,1.5),(0.6,1.5),(0.7,1.4),(0.8,1),(0.9,0.5),(1,0)])} \]

---

9 Sources: (Forrester 1969; Park et al. 2013)
Figure 6.5 Housing Land Multiplier

- **House Land Fraction Occupied** - is defined as the fraction of remaining available land to the total available area of land for residential development. Housing units are converted into residential land area by multiplying the housing stock by an average land per house. Since the total available land for residential purposes is fixed, housing land availability gradually decreases. (Units = Dmnl)

  \[ \text{House Land Fraction Occupied} = \frac{(\text{Land Per House} \times \text{Houses})}{\text{Land for Housing}} \]

The land per house is assumed to be constant over the entire time period and has a value of 2,300 square feet per house. The available land for housing is determined by the fraction of dedicated land for housing (0.1), as established by the City of Cambridge in 1990, and the total area around a half mile radius of Kendall Square.

  \[ \text{Land for Housing} = \text{Kendall Area} \times \text{Houses Land Fraction} \]

- **Housing Demolition** – Housing units are demolished at a rate proportional to the amount of housing units' times a housing demolition factor. (Units = Houses/Year)

  \[ \text{Housing Demolition} = \text{Houses} \times \text{Housing Demolition Normal} \]

- **Housing Demolition Normal** – is assumed to be constant at 0.0001. (Units = 1/Year).

- **Houses to Households Ratio** - ratio of number of housing units to the number of households required by the population. This dimensionless variable is used as the input for the attractiveness of housing multiplier. (Units = Dmnl)

  \[ \text{Houses to Households Ratio} = \text{Houses} / \text{Equilibrium Housing} \]
• **Attractiveness Housing Multiplier** – table function to determine the effect of the ratio of housing units to households on the attractiveness of housing development in the area. Values for this lookup table were taken from various urban models which followed Forrester's Urban Dynamics (Forrester 1969, Park 2011). Reasoning: people are attracted to move into the area as housing becomes available. The attractiveness to move in slowly grows as the area becomes more popular. However, if supply exceeds the demand, the attractiveness decreases.

\[
\text{Attractiveness of Housing Multiplier} = \]

\[
\text{WITH LOOKUP (Houses to Household Ratio,([(0,0)-(2,1)],(0,0.5),(0.5,0.502),(0.55,0.52),(0.6,0.547),(0.65,0.58),(0.7,0.615),(0.75,0.655),(0.8,0.705),(0.85,0.765),(0.9,0.828),(0.95,0.907),(1,1),(2,0.5)))}
\]

![Graph of Attractiveness of Housing Multiplier](image)

**Figure 6.6 Attractiveness of Housing Multiplier**

### 6.1.4 Employment

The following sub-model estimates the number of companies that are attracted to the area as a result of the attractiveness of available land, the available/potential labor force, and the general accessibility for the employees by auto, by transit, and by non-motorized trips. First, the model disaggregates business structures in two stocks: the more permanent companies (i.e. pharmaceuticals) and the start-ups. This distinction was made for two reasons. First, the average number of employees for these two “types” of businesses is very different. From historical data, the number of employees per company range from 1 employee to 1000, with MIT having as many as
8,500 employees. The second reason is the “stability of these firms”. While start-ups and small tech companies can easily move from one location to another, other firms, such as Draper Laboratories or the Volpe Center, cannot easily move either because of the operational costs or spaces constraints.

The model assumes an initial number of companies and start-ups which were present at the Kendall Square area in the 1990s and further assumes an average number of jobs per company/start-up. It should be noted that MIT is not accounted in this average, as it is an outlier in the area given the size and permanent character. In addition, only a fraction of the available land dedicated for industrial and commercial uses is considered, as it is believed that MIT owns much of the land and it is not available for private development. Furthermore, the model assumes that a fraction of the labor force within the metropolitan area (Boston, Cambridge, Newton, Brookline, Somerville, etc.) works in the Cambridge area and influences the generation of jobs at Kendall. Hence, indirectly, migration to the area is also driven by the amount of jobs available.

- **Companies** – The introduction of new companies to the Kendall Square area is determined both by the introduction of new permanent businesses and by the departure of companies. The initial number of companies in the area by 1990 is estimated to be 65 companies. (Units = Company)

  \[ \text{Companies} = \text{INTEG (Business Development-Business Demolition, Initial Companies)} \]

- **Business Development** – The introduction of new companies to the area is determined by the current number of companies times the business development multiplier which is a function of the attractiveness of the area based on its accessibility, the availability of land and the labor force. (Units = Company/Year)

  \[ \text{Business Development} = \text{Companies} \times \text{Business Development Normal} \times \text{Business Development Multiplier} \]

- **Business Development Normal** – It is an exogenous variable that determines the rate at which businesses are introduced in the area. It is assumed to be equal to 0.095 (Units = 1/Year).

- **Business Departure** – this variable captures the departure of firms from the area, as firms may not stay in the area indefinitely. Companies may relocate in other areas as economic conditions change or because they are no longer in business. (Units = Company/Year)

  \[ \text{Business Departure} = \text{Companies} \times \text{Business Demolition Normal} \]
- **Business Departure Normal** – It is an exogenous variable that determines the rate at which business leave the area. It is assumed to be equal to 0.009 (Units = 1/Year).

- **Start-Ups** – As in the case of companies, this stock is determined by the number of star-ups that decide to locate in the Kendall Square area and the departure of such firms. In order to initialize this stock, it is assumed that the initial number of start-ups is 45. (Units = Company)
  \[
  \text{Start-Ups} = \text{INTEG} (\text{Start-Ups Development}-\text{Start-Ups Departure}, \text{Initial Companies})
  \]

- **Start-Up Development** – The introduction of new start-ups to the area is a function of the number of start-ups currently in the area and the business development multiplier, as well as a development normal which is assumed to be 0.3 per year. (Units = Company/Year)
  \[
  \text{Start-Ups Development} = \text{Start-Ups} \times \text{Business Development Multiplier} \times \text{Start-Ups Development Normal}
  \]

- **Start-Ups Departure** – It is similar to the Business Departure variable and it assumes a departure normal of 0.09 (1/Year). (Units = Company/Year)
  \[
  \text{Start-Ups Departure} = \text{Start-Ups} \times \text{Start-Ups Departure Normal}
  \]
• **Total Business Structures** – Is the sum of the number of companies and start-ups at a given point in time. (Units = Company).

\[ \text{Total Business Structures} = \text{Companies} + \text{Start-Ups} \]

• **Business Land Fraction Occupied** – It is similar to the House Land Fraction Occupied, and is defined as the fraction of remaining available land to the total available area of land for industrial and commercial development. Companies are converted into business land area by multiplying the number of companies by an average land per business structure and by the land for business. This ratio gradually decreases as the total available area is fixed. (Units = Dmnl)

\[ \text{Business Land Fraction Occupied} = \]

\[ \frac{[(\text{Companies}\times \text{Land Per Business Structure}) + (\text{Start-Ups}\times \text{Land Per Start-Up Structure})]}{\text{Land for Business}} \]

The land per business structure and land per start-up structure has a value of 45,000 and 12,000 square feet respectively, and is assumed to be constant over the entire time period. The available land for business is determined by the fraction of dedicated land for business, as established by the City of Cambridge in 1990, considering the total area around a half mile radius of Kendall Square. As mentioned above, the fraction of land dedicated for business is reduced to account for the land that belongs to MIT; and it is assumed to have a value of 0.28. (Units = Dmnl)

\[ \text{Land for Business} = \text{Business Land Fraction} \times \text{Kendall Area} \]

• **Business Land Multiplier** – This table function represents the effect of the business land fraction occupied for the development of new business in the area. (Units = Dmnl)

\[ \text{Business Land Multiplier} = \]

\[ \text{WITH LOOKUP} (\text{Business Land Fraction Occupied},(((0,0)-(10,10]),(0,1),(0.1,1.15), (0.2,1.3),(0.3,1.4),(0.4,1.45),(0.5,1.4),(0.6,1.3),(0.7,0.9),(0.8,0.5),(0.9,0.25),(1,0))) \]
Figure 6.8 Business Land Multiplier

- **Business Development Multiplier** – This multiplier considers the effect of the labor force multiplier, the business land multiplier and the accessibility to jobs. (Units = Dmnl)

  Business Development Multiplier =  
  Business Labor Force Multiplier \times Business Land Multiplier \times Accessibility to Employment

- **Business Labor Force Multiplier** – This table function takes into consideration the effect of the labor force ratio on the attractiveness for businesses to locate in the area. If the labor force > jobs, then companies are more attracted to locate in Kendall as there is demand for jobs. (Units = Dmnl)

  Business Labor Force Multiplier =  
  WITH LOOKUP \((\text{Labor Force to Job Ratio,}\{(0,0)-(2,2)\},(0,0.2),(0.2,0.25),(0.4,0.35), (0.6,0.5),(0.8,0.7),(1,1),(1.2,1.34),(1.4,1.6),(1.6,1.8),(1.8,1.95),(2,2)\)\)
• **Labor Force to Job Ratio** – This ratio is used as an input for the attractiveness of labor force for the introduction of new businesses to the area. It takes into consideration the labor force within the metropolitan area and the number of jobs available, which in turn is determined by multiplying the total number of business structures (companies and startups) and the number of jobs for each. The number of jobs per business is determined by taking the average of employees per company from historical data, but excluding the employees at MIT. This variable has a value of 400 people for companies and 25 for startups. (Units = Dmnl)

\[
\text{Labor Force to Job Ratio} = \frac{\text{Labor Force}}{\text{Jobs}}
\]

In order to determine the labor force, an estimated number of work trips to the Cambridge area was obtained and later were multiplied by a fraction to estimate the number of work trips to the Kendall Square area. The total work trips was determined considering the number of working trips to the Cambridge area (home-based-work, HBW), which includes those who live and work in the area, as well as those workers who do not live in the area based on CTPP 2000. The total “metropolitan HBW trips” to Cambridge (109,500 trips) are then multiplied by a fraction of trips destined to the Kendall area, assumed to be 0.25. Past trends in the Cambridge area indicate that about 49 percent of the residents work in Cambridge, hence the model assumes that a fraction (0.49) of the Kendall population will work in the area. Based on CTPP 2000 and trends in Cambridge, this variable is assumed to be 0.49. (Units = People)
Labor Force =

\[ \text{Fraction of Cambridge Residents Working in Cambridge} \times \text{Population} + \text{Metropolitan Area HBW Trips} \times \text{Fraction of HBW Trips to Kendall} \]

Metropolitan Area HBW Trips =

\[ 109500 + \text{ramp}(1095 \times \text{Metropolitan Population}, 1990, 2040) \]

Finally, jobs are determined by adding the total jobs generated per company and per start-up, plus those at MIT. The latter is considered to be constant over the entire time period at a value of 8,500 people. (Units = People)

\[ \text{Jobs} = (\text{Companies} \times \text{Jobs per Company}) + (\text{Start-Ups} \times \text{Jobs per Start-Up}) + \text{MIT Jobs} \]

- **Attractiveness of Job Multiplier** – is a table function which determines the effect of the job market in the attractiveness of the area. This variable has the opposite effect of the Business Labor Force Multiplier; as labor force > jobs, the less attractive is the area for people to move in as there is competition for the available jobs. (Units = Dmnl)

\[ \text{Attractiveness of Job Multiplier} = \]

\[ \text{WITH LOOKUP} (\text{Labor Force to Job Ratio}, [(0,0)-(2,2)],(0,2),(0.2,1.95),(0.4, 1.8), (0.6,1.6),(0.8,1.35),(1,1),(1.2,0.5),(1.4,0.3),(1.6,0.2),(1.8,0.15), (2,0.1)) \]

![Figure 6.10 Attractiveness of Job Multiplier](image)

- **Accessibility to Employment** – This variable is a function of the attractiveness of auto trips, transit trips, and non-motorized trips to the Kendall Square area. As accessibility to
the area decreases, companies are not encouraged to move to the area. It is to be noted that auto trips may be constrained by parking policies. Transit trips are equally constrained by transit capacities. On the other hand, non-motorized trips are constrained by existing residents within walking or biking distance. The attractiveness of each of these trips are defined in the next sub-model. (Units = Dmnl)

\[
\text{Accessibility to Employment} = \\
\text{Accessibility of Auto Trips to Kendall} + \text{Accessibility of Transit Trips to Kendall} + \\
\text{Attractiveness of Non-Motorized Trips}
\]

6.1.5 Travel Demand

This last sub-model aims at describing the demand for transportation travel from and to the Kendall Area. It consists of four stocks: (1) the total number of auto trips TO, (2) transit trips TO, (3) transit trips FROM, and (4) non-motorized (NM) trips in the Kendall Square, all during the morning peak period. The first two stocks relate to the employees coming to the area, while the third influences the attractiveness of transit for the residents in the area. The forth stock represents all those workers and residents who walk or bike into the area. As was pointed out in Chapter 4, there have been recent trends in the area which indicate that many residents who work in the area walk or bike to work, while there are other workers who live in close proximity (not necessarily within the catchment area) who also walk/bike to work (Peralta-Quirós 2013). As it has also been mentioned, proximity by foot to the work place influences residents' decisions to move to the area, given that it translates into an increase in accessibility.

\[
\text{Accessibility to Employment} \text{ is measured as the sum of the Accessibility of Auto Trips to Kendall, Accessibility of Transit Access to Kendall, and Attractiveness of Non-Motorized Trips. On the other hand, Accessibility for Residents is equal to the Attractiveness of Transit Access from Kendall. These two quantities are used to estimate the general area accessibility using the following equation.}
\]

\[
\text{Area Accessibility} = \text{Accessibility to Employment} + \text{Accessibility for Residents}
\]

It should be noted that, the accessibility to employment influences the business development multiplier mentioned in the employment section.

People may be attracted to move to the area if the ratio of jobs and population is large: as there are more jobs compared to the population within a catchment area, the more likely people will be attracted to live there, if housing is available.
The number of work trips attracted to the Kendall Square area is proportional to the number of jobs in the area. In order to determine the number of auto, transit, walk, and bike trips, this amount is multiplied by their respective mode shares, which is taken from Table 4.9 based on the modal split at place of work for 1990 and assumed to be constant over the entire period.

\[
\text{Total Work Trips to Attracted to Destination} = \text{Jobs (Units = People)} \\
\text{Auto Mode Share (Workers)} = 67.4\% \\
\text{Transit Mode Share (Workers)} = 20.8\% \\
\text{NM Mode Share (Workers)} = 11.8\%
\]

6.1.5.1 Auto Trips TO

- **Auto Trips to Kendall (AM PEAK)** – The number of auto trips allowed in the Kendall area and is determined by the incoming auto trips, the expired trips, and the constraint defined by the availability of parking spaces. The initial number of auto trips into Kendall Square is assumed to be 31,051, which combines the drove alone and carpool trips observed in 1990 (Table 4.9). (Units = People)

\[
\text{Auto Trips to Kendall (AM PEAK)} = \text{INTEG (New Auto Trips-Expired Auto Trips,Initial Auto Trips)}
\]
**Figure 6.11 Stock for Auto Trips to Kendall Square**

- **New Auto Trips** – Determines the new auto trips attracted to the area every year based on the availability of parking, the total number of auto work trips produced by the total jobs in the area, and the attractiveness of auto trips, which is a function of the parking supply. (Units = People/Year)

  \[
  \text{New Auto Trips} = (\text{Total Auto Trips (Workers)} - \text{Auto Trips to Kendall (AM PEAK)}) \times \text{Accessibility to Auto Trips to Kendall} \times \text{Auto Trips Normal}
  \]

  The variable year is used as a normalizing variable and takes a value of 0.16.

- **Attractiveness of Auto Trips to Kendall** – It is a table function which determines the effect of availability of parking on the attractiveness of auto trips to the area. In general, as parking becomes limited, fewer trips will be allowed by auto.
Accessibility to Auto Trips to Kendall =

WITH LOOKUP (Auto Trips to Parking Ratio,\((0,0)-(1.5,1.5)\), (0,1), (0.4,1), (0.6,1), (0.83,0.98), (0.931193,0.907895), (0.958716,0.65), (1,0))

![Graph](image)

Figure 6.12 Attractiveness of Auto Trips to Kendall Square

- **Auto Trips to Parking Ratio** - It determines the ratio of actual auto trips to the parking supply; assuming a parking supply (non-residential use) of 24,196 spaces.

  \[
  \text{Auto Trips to Parking Ratio} = \begin{cases} 
  1, & \text{if } \frac{\text{Auto Trips to Kendall (AM PEAK)}}{\text{Parking Supply}} > 1 \\
  \text{Auto Trips to Kendall (AM PEAK)}/\text{Parking Supply}, & \text{otherwise}
  \end{cases}
  \]

- **Expired Auto Trips** - It determines the number of auto trips that leave the area in a given year, given the effects of parking availability ("Effect of Congestion"). This variable captures those employees that leave the area to go work somewhere else or those who decide to switch mode of transport as parking becomes unavailable. The decision to switch mode based on socio-economic variables is not considered in the model, but captured through a delay function using the number of auto trips and an expiration normal variable, which takes a values of 0.035. (Units – People/Year)

  \[
  \text{Expired Auto Trips} = (\text{Auto Trips to Kendall (AM PEAK) - Parking Supply})*\text{Auto Trips Expiration Normal}^*\text{Effect of Congestion (Workers)}
  \]
- **Effect of Congestion (Workers)** – This look-up table considers the effect of availability of parking on the decrease in auto trips into the area.

\[
\text{Effect of Congestion (Workers) } = \text{WITH LOOKUP (Auto Trips to Parking Ratio, } \hspace{0.5cm} \\
((0,0),(1,1)), (0,0), (0.15, 0.0013), (0.33, 0.0088), (0.486, 0.0219), (0.813, 0.0614), (0.963, 0.315), (1, 1)))
\]

![Figure 6.13 Effect of Congestion on Auto Trips](image)

- **Unsatisfied Auto Trips (Workers)** – This variable captures the difference between the total auto trips in and the actual number of auto trips allowed. If the total auto trips attracted to the area is larger than the parking supply, there will be a number of trips that will not be allowed to come in the area and must find alternative ways. This model is structured so that all these trips are transfer to transit, as the likelihood of walking and biking from abutting towns is small. (Units, People)

\[
\text{Unsatisfied Auto Trips (Workers) } = \text{IF THEN ELSE(Total Auto Trips (Workers) > Auto Trips to Kendall (AM PEAK), Total Auto Trips (Workers) - Auto Trips to Kendall (AM PEAK), 0 )}
\]

- **Total Auto Trips (Workers)** – It captures the number of trips that are attracted to the Kendall Square area. It considers auto trips as determined by the number of jobs in the area, as well as a fraction of the transit trips that may not be served by the current transit infrastructure due to capacity limitations. (Units = People)
Total Auto Trips (Workers) =
IF THEN ELSE(Transfer from Transit to Auto<0, Auto Trips (Workers), Transfer from Transit to Auto + Auto Trips (Workers))

- **Auto Trips (Workers)** – This is the fraction of auto trips from the total work trips attracted to Kendall Square. (Units People)

\[Auto Trips (Workers) = \frac{Total Work Trips Attracted to Destination \times Auto Mode Share (Workers)}{Total Work Trips Attracted to Destination}\]

- **Total Work Trips Attracted to Destination** – This is the number of working trips attracted to the Kendall Square area and is a function of the number of jobs.

\[Total Work Trips Attracted to Destination = Jobs\]

- **Transfer from Transit to Auto** – This variable aims at capturing those transit riders that cannot use public transportation as capacity is reached and must use alternative modes. Since not everyone will switch to auto use, only a percent of the trips are allowed to transfer to auto; this fraction of transfers is assumed to be 0.25. (Units = People)

\[Transfer from Transit to Auto = \frac{Fraction of Transfers from Transit to Auto \times Unsatisfied Transit Trips (Workers)}{New Ridership (Workers) - Lost Ridership (Workers)}\]

6.1.5.2 **Transit Trips TO**

- **Transit Trips to Kendall (AM PEAK)** – Similar to the auto trips to Kendall, transit alightings at Kendall Square station are determined by actual ridership, which is a function of the total transit trips into the area and the capacity of the system and the ridership lost due to crowding in the system. The initial ridership at Kendall is assumed to be 7,588 people, which is a fraction of the average daily ridership estimated in 1990. Ridership data collected and analyzed for April 2012 (Block-Schatcter, 2013) was used to determine the fraction of the trips alighting at Kendall during the morning period. (Units = People)

\[Transit Trips to Kendall (AM PEAK) = \text{INTEG (New Ridership (Workers) - Lost Ridership (Workers)), Initial Ridership (Workers)}\]

- **New Ridership (Workers)** – It represents the number of new riders allowed into the system. The number of passengers attracted to the system is determined in turn by the capacity of the system. As the capacity of the system is reached, the attractiveness of using transit reduces. Since there are riders which have no alternative other than transit ("captive
riders") or switching to another mode (e.g. auto) may not be possible, a normalizing variable is introduced with a value of 0.035. (Units = People/Year)

\[
\text{New Ridership (Workers)} = \\
\text{ABS(} \text{Total Transit Trips (Workers)} - \text{Transit Trips to Kendall(AM PEAK)}\text{)} \times \text{Transit Multiplier (Workers)} \times \text{Transit Workers Normal}
\]

- **Transit Multiplier (Workers)** - It is a table function which measures the effect of the ridership to capacity ratio on the allowed number of riders in the system. (Units = Dmnl)

\[
\text{Transit Multiplier (Workers)} = \\
\text{WITH LOOKUP (Ridership to Capacity Ratio (Workers), \[((0,0)-(1,2)],(0,1), (0,1), (0.2,1), (0.3,1), (0.4,0.96), (0.6,0.93), (0.7,0.85), (0.8,0.65), (0.9,0.45), (1,0))\))}
\]

![Figure 6.14 Transit Multiplier (Workers)](image)

- **Ridership to Capacity Ratio (Workers)** - It is the ratio of the ridership in a given year to the capacity of the network. The model only allows for the capacity to reach 1. (Units = Dmnl)

\[
\text{Ridership to Capacity Ratio (Workers)} = \\
\text{IF THEN ELSE(Transit Trips to Kendall (AM PEAK)/Transit Capacity (AM PEAK)>1, 1, Transit Trips to Kendall (AM PEAK)/Transit Capacity (AM PEAK))}
\]

- **Transit Capacity (AM PEAK)** - It is a function of the frequency (trains per hour), the number of vehicles (9 vehicles per train), the number of passengers per vehicle (55
passengers per vehicle), the duration of the peak period (2 hours), and a load factor (1.3). The duration of the peak period is assumed to be two hours, as not everyone gets in at the same time and firms allow for more flexible schedules. In addition, the load factor allows for additional riders as trains can accommodate additional riders. (Units = People)

Transit Capacity (AM PEAK) = 
Frequency*Number of Vehicles*Passengers Per Vehicle*Peak Period Duration*Load Factor

- **Lost Ridership (Workers)** - It determines the number of riders that are lost every year, which is normalized with an adjustment rate (0.005) as people cannot switch mode that easily given income and auto availability, which limits people’s willingness to switch mode. (Units = People/Year)

Lost Ridership (Workers) = 
Transit Trips to Kendall (AM PEAK)*Crowding Effects (Workers)* Adjustment Rate

- **Crowding Effects (Workers)** - It is a table function that considers the effect of crowding on ridership not served. (Units = Dmnl)

Crowding Effects (Workers) = 
WITH LOOKUP (Ridership to Capacity Ratio (Workers), [(0,0)-(1,1)],(0,0), (0.153,0.0013),(0.333,0.00526),(0.517,0.01053),(0.7003,0.0184),(0.881,0.118),(0.954,0.298),(0.985,0.605),(1,1))

![Crowding Effects (Workers)](image)

- **Total Transit Trips (Workers)** - It is similar to the total auto trips in, representing the total amount of work trips which use public transportation as a means of transport. It
considers those transit trips generated by the jobs in the area, as well as those trips which are transferred from auto to transit. (Units = People)

\[
Total\ Transit\ Trips\ (Workers) = \\
\text{IF \ THEN \ ELSE}(\text{Transfer\ from\ Auto\ to\ Transit\ Trips\ (Workers)} < 0, \text{Transit\ Trips\ (Workers)}, \text{Transfer\ from\ Auto\ to\ Transit\ Trips\ (Workers)} + \text{Transit\ Trips\ (Workers)})
\]

- **Transit Trips (Workers)** – It is the fraction of transit trips from the total work trips attracted to Kendall Square (Units = People)

\[
\text{Transit\ Trips\ (Workers)} = \\
\text{Total\ Work\ Trips\ to\ Attracted\ to\ Destination} \times \text{Transit\ Mode\ Share\ (Workers)}
\]

- **Transfer from Auto to Transit Trips (Workers)** – It is the number of unsatisfied auto trips. (Units = People)

\[
\text{Transfer\ from\ Auto\ to\ Transit\ Trips\ (Workers)} = \text{Unsatisfied\ Auto\ Trips\ (Workers)}
\]

- **Unserved Transit Trips (Workers)** – It is the difference between the desired transit trips (total transit trips) and the actual transit trips to Kendall. Contrary to the unsatisfied auto trips, which assumed that all trips will be transferred to transit, these unsatisfied transit trips will be distributed to auto trips, other transit modes, and walk/bike trips as change in mode is a function of socio-economic characteristics of the rider. (Units = People)

\[
\text{Unsatisfied\ Transit\ Trips\ (Workers)} = \\
\text{Total\ Transit\ Trips\ (Workers)} - \text{Transit\ Trips\ to\ Kendall\ (AM\ PEAK)}
\]

- **Transfer from Transit to Transit (Other)** – represents the fraction of transfer trips from transit to other transit systems (e.g. buses). It assumes that 65% of the unsatisfied trips will be transferred to these other systems. (Units = People)

\[
\text{Transfer\ from\ Transit\ to\ Transit\ (Other)} = \\
\text{Unsatisfied\ Transit\ Trips\ (Workers)} \times \text{Fraction\ of\ Transfers\ from\ Transit\ to\ Transit}
\]

- **Transfer from Transit to NM** – It represents the fraction of users that switch from transit to walking or biking, assuming that 10% of the users transfer to bike/walk. (Units = People)

\[
\text{Transfer\ from\ Transit\ to\ NM} = \\
\text{Unserved\ Transit\ Trips\ (Workers)} \times \text{Fraction\ of\ Transfer\ from\ Transit\ to\ NM}
\]

- **Attractiveness of Transit Access to Kendall** – This table function measures the effect of the capacity of the system to the attractiveness of transit access for employees. (Units = Dmnl)

\[
\text{Attractiveness\ of\ Transit\ Access\ to\ Kendall} = \\
\text{...}
\]
WITH LOOKUP (Ridership to Capacity Ratio (Workers), [[(0,0)-(1.5,1.5)],
(0,1),(0.4,1),(0.6,1),(0.8,1),(0.9037,0.881579),(0.981651,0.611842),(1,0)])

Figure 6.16 Attractiveness of Transit Access to Kendall Square

Figure 6.17 Stock for Transit Trips to Kendall Square
6.1.5.3 Transit Trips FROM\(^{10}\)

- **Transit Trips from Kendall (AM PEAK)** - This variable captures the annual ridership boarding at Kendall Square in the morning period. It is a function of the total transit trips generated in the area from the residential side and the capacity of the system, and the lost ridership due to crowding in the system. The initial ridership is assumed to be 3,099 people, which is a fraction of the average daily ridership estimated in 1990 (Block-Schatcter, 2013).
  \[(\text{Units} = \text{People})\]
  \[
  \text{Transit Trips from Kendall (AM PEAK)} = \text{INTEG (New Ridership (Residents)-Lost Ridership (Residents),Initial Ridership (Residents))}
  \]

- **New Ridership (Residents)** - It represents the number of new riders allowed into the system, which is a function of the capacity of the system, assuming a normal variables of 0.045.
  \[
  \text{Ridership (Residents)} = \text{ABS(Total Transit (Residents)-Transit Trips From Kendall (AM PEAK))*Transit Multiplier (Residents)*Transit Residents Normal}
  \]

- **Transit Multiplier (Residents)** - Same as for workers.

- **Ridership to Capacity Ratio (Residents)** - same as for workers.

- **Lost Ridership (Residents)** - It determines the number of riders that are lost yearly and is normalized with an adjustment rate of 0.00005. (Units = People/Year)
  \[
  \text{Lost Ridership (Residents)} = \text{Transit Trips to Kendall (AM PEAK)*Crowding Effects (Residents)* Adjustment Rate}
  \]

- **Crowding Effects (Residents)** - Same as for workers

- **Transit Trips (Residents)** - It is the fraction of total home-based-work trips from the residential side, assuming a transit mode share for the residents of 25.1 percent. A second assumption is made since note all transit trips out of the area will be made through the Red Line. Therefore, it is assumed that 50% of desired transit trips are using the Red Line. (Units People)
  \[
  \text{Transit Trips (Residents)} = \text{Population*Transit Mode Share (Residents)*Fraction of Red Line Transit Trips}
  \]

---

\(^{10}\) Most of these variables are similar to those presented in the model structure for transit trips TO Kendall.
- **Attractiveness of Transit Access from Kendall** - Same as for workers.
- **Accessibility for Residents** - This variable is a function of the attractiveness of transit access from the Kendall Square area; as accessibility for the residents for the residents decreases, the less attractive it becomes to move to the area. (Units = Dmnl)

\[
\text{Accessibility for Residents} = \text{Attractiveness of Transit Access from Kendall}
\]

6.1.5.4 **Non-Motorized Trips**

- **Non-Motorized (NM) Trips** - This stock represents the sum of non-motorized (walk/bike) working trips, produced by both the job and household sector, that is by workers and residents in the area. Initial non-motorized trips is assumed to be 1,724, which represents the share of walking and biking trips obtained from CTPP1990 (See Table 4.9). (Units = People)

\[
\text{Non-Motorized Trips} = \text{INTEG (New NM Trips-Expired NM,1724)}
\]
• **New NM Trips** – It represents the new non-motorized trips, which is a function of the trips generated by the residential and labor market minus the number of existing non-motorized trips at a given time, normalized yearly (0.4). (Units = People/Year)

\[
\text{New NM Trips} = (\text{NM Trips (Workers)} + \text{NM Trips (Residents)} - \text{Non-Motorized Trips}) \times \text{NM Trips Normal}
\]

• **Expired NM Trips** – It represents the number of users that no longer travel by foot or bike. This parameter is normalized yearly at 0.2. (Units = People/Year)

\[
\text{Expired NM} = \text{Non-Motorized Trips} \times \text{NM Trips Expiration Normal}
\]

• **NM Trips (Residents)** – It is the number of walking and biking work trips generated by the residential side. It is assumed that residents within the catchment area of Kendall decided to locate in the area precisely because they have easy access to jobs since they can walk or bike to their employment location. In order to determine this parameter, the population within the catchment area is multiplied by the share of working trips which take place by walking and biking, assuming a mode share of 29.2 percent (Table 4.9). (Units = People)

\[
\text{NM Trips (Residents)} = \text{NM Mode Share (Residents)} \times \text{Population}
\]

• **NM Trips (Workers)** – It represents the number of non-motorized trips that are attracted to the area based on the number of jobs and the transfer of transit trips to non-motorized trips due to capacity constraints in the transit network. NM Trips generated by the total work trips attracted to this destination, account for those trips that are produced outside the catchment area, assuming a mode share of 11.8 percent (Table 4.9).

\[
\text{NM Trips (Workers)} = \text{Total Work Trips to Attracted to Destination} \times \text{NM Mode Share (Workers)} + \text{Transfer from Transit to NM}
\]

• **Attractiveness of Non-Motorized Trips** – This variable captures the effect of the attractiveness of walking or biking on the decision of firms to locate in the area, taking into account the growth in housing stock. It is assumed that an increase in housing stock will increase the accessibility of employees, hence increase the attractiveness of firms to locate in the area. (Units = Dmnl)
Growth of Housing Stock = (Housing Construction*Year Adjustment/Houses)

Attractiveness of Non-Motorized Trips =
WITH LOOKUP (1+Growth of Housing Stock,[[0,0.27],[0.28,0.28],[0.51,0.29],[0.734,0.325],[0.86,0.39],[1,0.5],[1.06,0.767],[1.21,0.92],[1.44,0.98],[1.77,0.99],[2,1]])

Figure 6.19 Effect of Housing growth on employees accessibility

Figure 6.20 Stock for Non-motorized Trips
6.2. Policy Applications

One of the purposes of government policies relating to urban cities is to manage properly the balance between economy growth, social welfare, and respect for the environment. In some instances, facilitating population growth may fit well into the above goal of satisfying the three E's of Economy, Environment, and Equity. The method to achieve this is to trigger one of the reinforcing loops mentioned in Chapter 5, particularly R1, R3, R5, R7 which relate to the housing supply, the number of jobs and the services provided. However, one should remember that these policies also trigger the related balancing loops. As the urban population grows, related parameters decrease, such as the demand for labor, housing supply rate, and the quality and quantity of services provided by the transport sector. These parameters in turn induce a decrease in urban attractiveness and/or population inflow.

Increasing employment densities around transit stations is not likely to take care of continuous growth, even if zoning around stations favors other uses other than residential. Existing zoning that allows commercial or industrial use may not, by itself, be sufficient to spur employment growth. Often, more explicit strategies to encourage business development are necessary. Specific policies need to be introduced in order to encourage this type of development and transit ridership around transit stations. For example, restricting the availability or raising the cost of parking could encourage ridership. Other land use policies, such as waiving floor-area-ratio and height restrictions or providing development, incentives can also encourage increases in densities and transit use. In addition, strategies to encourage densities in Kendall Square must focus at least as much on residential density as on employment densities. In the end, a combination of parking, zoning, and urban design policies potentially could encourage both residential and commercial development around new transit stations.

6.2.1 Land Use Policies: Mixed Development

The availability of land could be one of the main constraints for the development of housing and economic activity. However, the introduction of land use policies which allow for higher densities ("vertical construction") will most likely foster further development and allow an increase of "new comers" to the area.
If the benefits of transit investments associated to the reduction of auto trips into an area were to be assessed, changes in density would represent a better measure than, for example, changes in property values, even though changes in property values may be a better indicator of the economic development impact of transit investments (Giuliano and Agarwal 2010). Economic theory suggests that an increase in demand for land puts upward pressure on land values and induces development unless restricted by zoning or other constraints. Thus, increased density around a new transit station would mean two things: (1) that the demand for land around the station has increased and (2) that new development was permitted.

An increase in land values without an increase in density would still reflect an increase in demand for land around transit stations, but less potential to reduce auto use because the number of people or jobs near the transit station (and therefore likely to use transit) would not necessarily increase.

6.2.2 Parking Policies

Strategies to increase parking costs or the probability that all drivers would have to pay for parking are found to be more effective in increasing transit mode share than increasing the level of transit service in terms of frequency and accessibility (Taylor and Fink 2003). In addition, Badland showed that work-related commuting appears to be a product in-part of convenience and auto accessibility constraints. When a public transport stop is near and convenient for people, they are more likely to travel via that mode, whereas having car parking available at the worksite is positively associated with work-related car travel (Badland, Garrett, and Schofield 2010).

In addition to the availability of land, auto accessibility is a strong constraint for the attractiveness of business development. However, if transit is accessible, then the area would still be attractive for companies to establish themselves in the area, as long as the capacity of the network allows for an increased inflow of riders. Therefore, all else being equal, we can expect that as parking becomes limited, the inflow of new companies into the area reduces. However, if transit capacity is increased, or walking and biking is a convenient option, the system can capture those “unsatisfied trips” and compensate for the decrease in auto accessibility. Businesses located in areas where transit services have been reduced are likely to be confronted with an increasingly constricted pool of qualified employees, given that many workers might find their access to job locations similarly curtailed.
6.2.3 Combination of Scenarios

A combination of mix development and parking constraints policies around transit station will not only increase densities, but will also influence residents and workers mode choice. Higher densities at stations create a large market for workers, residents, or customers that can easily access transit, thus reducing auto trips. The recent trend in the last few years, where there has been an increase in the transit-dependent-by-choice population, defined earlier as those whose lifestyle choice is to live in a more pedestrian and bicycle-friendly urban areas, instead of driving to their destinations, supports this latter point and as a result, people have started to locate near their job location.

By combining these types of policy measures, one can address several problems in urban areas regarding congestion and parking. Congestion is particularly linked with motorization and the diffusion of the automobile, which increases the demand for transportation infrastructure. The increase in motorization expands the demand for parking space as vehicles spend most of the time parked, creating space consumption problems particularly in central areas. In addition, the time spent looking for parking creates additional delays, increases the environmental impact, and impairs local traffic. Concentrating growth in infill locations and near transit, in the form of transit oriented development, may reduce auto use in the area, though significant reductions may be difficult to achieve if parking remains free and oversupplied. Lastly, minimum parking requirements not only encourage auto trips, but also create a barrier for infill development. Although benefits of parking maximums are not well-documented, there is some evidence that parking maximums lead to marginal increases in transit ridership and decreases in vehicle congestion.

6.3. Model Assessment

There are many challenges in modeling the research question of interest in this thesis, and explicit efforts to mitigate the impact of such challenges have been built in the design of this model.

The total ridership, housing stock, jobs, population, or any other metric are not intended to be a prediction, but rather a relative measure that enables the user to analyze the patterns of development over time and the differences among scenarios. The shape of the curves is more important than the intercept or extreme values. Confidence in the existence of several interactions, isolated or compounded, and the directionality of the resulting change are more important than the
numeric relationship between them. In addition, it allows for the model to be used as a tool for comparing the relative benefits of various scenarios.

In reality, the system is subjected to other factors that are not accounted for in the model due to this research scope and for simplicity, as this is a first attempt to understand the dynamics and patterns of growth in the Kendall area. Among the factors explicitly not represented in the model, we can highlight:

- The model does not include the complete transportation network (i.e. bus lines, highway links) for the area, nor parameters that influence the attractiveness of private/public transportation such as auto ownership or costs and times of travel. Undoubtedly, these parameters shape mode share, as users are transferred from one mode to the other as capacities are reached (auto and transit) or travel times increase or decrease. One reason not to include these is that the model is not intended to be a discrete choice model. Still, it would be ideal to introduce stocks which represent mode shares for buses, transit, walking, biking, and auto trips, taking into account network conditions and logit parameters.

- Socio-economic characteristics of the population and migration models – As pointed in previous chapters, people migrate in and out at rates that are affected by how attractive the zone is to live in and their socio-economic conditions. However, the model does not include income levels for the population, changes in perceived attractiveness in the Kendall Square area and in other competitive areas, as a function of rent prices, crime rates, congestion, and other economic conditions. The only variable considered that relates to zones "outside the system" is the population in the metropolitan area.

- The model does not include the national and regional economic conditions of the area. Therefore, it fails to capture the 2008 financial crisis experienced in the U.S. and the changes in socio-economics of the population.

The model presented in this thesis is still "work in progress" and has more shortcomings than one would like. However it is argued that it represents a significant step forward as the results extend beyond absolute numbers. In addition, it is considered to be genuinely a practical tool that can help policy makers understand the dynamics of cities and towns, and as a result not only account for the dynamics of change at play, but adopt a pro-active approach to identify policy triggers.
In this chapter the simulation results for the executable model are discussed, including the validation of the model based on reported data for all the stocks in the model. Based on the initial simulation, the patterns of growth experienced in the Kendall Square area are examined in order to identify potential policy measures that will allow for a continuous growth in the area. Additional simulation runs are conducted to test and compare the different scenarios and test for sensitivities in the model. Finally, relevant conclusions and policy suggestions are summarized.

7.1. Model Validation

The model was validated with historical data gathered from 1990 to 2010, though no historic data for the number of housing units by census tract for 2000 nor for 2010 auto trips was found, still the trend for housing stock is rather constant as demonstrated in the increase in the number of households reported (Table 4.7). From Table 7.1 it can be observed that for the year 2000, the error term for most of the variables is less than 10 percent, except for the number of jobs, as the error is about 26.4 percent above the reported data. It is to be noted that since no macroeconomic parameters are included, the impact of the 2000 economic crisis is not included. For 2010, most of the errors are within 1 percent above or below of reported data, except for non-motorized trips, where the error increases by 15.9 percent. From these results, it seems like the model is effective enough to simulate the patterns of growth observed in Kendall Square, as errors are between 1 and 2 percent for almost all variables in 2010.

Table 7.1 Comparison of Model Outputs with Reported Data

<table>
<thead>
<tr>
<th>Index</th>
<th>2000</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model Output</td>
<td>Reported Data</td>
</tr>
<tr>
<td>Population</td>
<td>13,874</td>
<td>13,965</td>
</tr>
<tr>
<td>Housing Units</td>
<td>5,232</td>
<td>N/A</td>
</tr>
<tr>
<td>Jobs</td>
<td>47,375</td>
<td>37,476</td>
</tr>
<tr>
<td>Transit Ridership TO</td>
<td>8,277</td>
<td>8,100</td>
</tr>
<tr>
<td>Transit Ridership FROM</td>
<td>3,548</td>
<td>3,308</td>
</tr>
<tr>
<td>Non-Motorized Trips</td>
<td>6,589</td>
<td>6,150</td>
</tr>
<tr>
<td>Auto Trips to Kendall</td>
<td>29,001</td>
<td>29,048</td>
</tr>
</tbody>
</table>
Figures 7.1 through 7.3 present the simulation results for the population, housing, and jobs obtained from the model. As mentioned above, the model is able to simulate actual trends observed for the population and housing stock, though the error for the number of jobs is high for the period between 1990 and 2000. In the case of the population, the model suggests that the area will experience continuous growth, though the rate of growth will begin to decrease around 2015.

![Population Stock Graph](image)

**Figure 7.1 Model Validation: Population Stock**

Though no data was available for the number of housing units per census tract in 2000, the model is able to estimate the number of housing units for 2010 with an error of less than 0.1 percent. From Figure 7.2, it can be observed that during the entire time period, the number of housing units has been increasing, though at a decreasing rate as availability of land constrains the construction of new housing units. Hence, the decrease in population growth observed in the previous figure (7.1).
The discrepancies in the number of jobs between 1990 and 2000 is most likely explained by the exclusion in the model of national and regional economic parameters such as gross domestic product (GDP), unemployment rates, etc., which would have captured the economic crisis experienced during the last decade. This financial crisis definitely affected the employment and housing sector, slowing the growth of jobs and the rate at which housing units were built, as well as the socio-economic conditions of households. By excluding these overall economic parameters, the first years of the simulation result in a sudden increase in the number of jobs, as there is land for development. During those first years, most of the space available for businesses is consumed, hence decreasing the rate at which firms are introduced in the area. From Figure 7.3 it can be observe that jobs are increasing during the entire period, though limited land, accessibility, and labor force, amongst others constrain any additional growth.
Figures 7.4 and 7.5 present the stocks for transit ridership to and from the Kendall Square area, respectively. The model assumes that the frequency of service has been constant as no changes in frequency have been reported during the last 20 years. Transit ridership to Kendall Square experiences an S-shape growth as ridership reaches the network capacity set at 12,870 riders (See Section 5.3.3). From Figure 7.4 we can observe that transit ridership increases at an increasing rate during the first 20 years, though it starts to increase at a decreasing rate after 2010 when capacity constraints reduce attractiveness of transit. As it is observed in Table 7.1, the error for 2010 transit ridership to Kendall is just 1.7 percent above observed data. The model further suggests that transit ridership from the residential side is constantly increasing during the entire time period; by 2040, ridership is less than half of the capacity. For this parameter, the error term obtained for the 2010 simulation output is 2.1 percent above the observed data.
Figure 7.4 Model Validation: Transit Trips TO Kendall Square Stock

Figure 7.5 Model Validation: Transit Trips FROM Kendall Square Stock
As mentioned earlier in Chapter 4, Kendall Square has experienced an increase in the number of biking and walking trips. The increase in non-motorized trips is captured in the model (Figure 7.6) with an increase in 2000 of 22.5 percent compared to the previous decade and 7.6 percent between 2000 and 2010. However, the model do exhibit errors in the simulated output as the error term for the 2010 model output is 15.9 percent above the reported data. This error may be attributed to the fact that the model is not capturing changes in population and housing stock outside the Kendall Square area, as the model is essentially a two-zone model: Kendall and the rest of the world. From previous discussion, Cambridge has experience an increase in population during the last 20 years, which has been accompanied with an increase in the number of residents living and working in the area, which in turn has resulted in an increase in the number of non-motorized trips. By excluding demographic changes and the attractiveness of other zones outside the study area, we are not able to capture those additional trips that are made to Kendall, which most likely increase the general attractiveness of Kendall Square and hence, allows for additional job growth.

![Non-Motorized Trips](image)

*Figure 7.6 Non-Motorized Trips in Kendall Square Stock*
It should be noted that under no condition is this model intended for actual prediction or forecast of the various parameters, but rather it provides a relative measure which enables analysis of the patterns and trends of development over time, as well as the testing of various policies and scenarios. These policies and different scenarios are discussed in the next section.

7.2. Model Analysis: Understanding Kendall's Dynamics of Change

This thesis has intended to highlight the different key drivers that have contributed to the development of Kendall Square in the last two decades and which may allow further growth in the area in the future, while respecting the constraints of growth. The major strength of this model is its ability to illustrate in a concise manner how the feedback structure of the system can endogenously generate growth, stagnation, and/or decay.

MIT's proximity, the accessibility provided by auto, by transit services through the MBTA Red Line, and by non-motorized means, plus the availability of space for development, have been identified as initial triggers for the employment growth observed in the area. These drivers coupled with MIT's land development plans, the numerous companies and start-up choosing to locate in the area, and the immigration of a pool of young professionals who have decided to locate near the area, are part of the current dynamics of Kendall Square. However, the relationship among these factors and their compounded impacts on growth are not easily understood.

For many, Kendall Square has been a success story, in terms of the job and housing development that has occurred over the past years. However, it is hard to estimate whether this can be sustained since land is not infinite, behaviors change, and infrastructure capacities may be reached. In the end, the complexities of the issues are not intuitive. What may limit a continuous growth in the area ultimately depends on the accessibility to and from the area, the availability of land for development, and the provision of adequate housing. Figure 7.7 shows the evolution estimated for population, housing stock, and employment in the area for the initial simulation (base case scenario). As discussed in the previous section, the three stocks experience an increase from the initial input values, though the availability of land for business and housing development slows the rate at which jobs and housing units are created, particularly after year 2015 (See Appendix).

During the early years of the simulation, the growth in job opportunities in the area attracted people to locate in the area. However, population did not increase exponentially as the limited housing stock controlled the number of people who could actually relocate in the area. More
business structures increase the attractiveness to future companies and start-ups to locate in the area. The continuous growth in demand for housing units, coupled with existing increase in the construction of housing units, increases the attractiveness to future home developers. The increase in the housing and employment sector, in turn, lead to a growth in population via migration.

As the process of growth continues, land becomes scarce, leading to a decrease in business and housing development. Naturally, as the stock of housing and business structures grow, the fraction of land occupied increases. However, now, the effect of space limitations outweighs the gain from increased regional attractiveness; thereby slowing the rate of housing and business construction until the available land is almost completely full. These dynamics are presented in Figures 7.8 and 7.9. The increase in the number of jobs during the first 20 years results in the consumption of about 31.8 percent of the remaining available land, hence the continuous decrease in the effect of land availability in the attractiveness for development (Figure 7.9). As most of the land is occupied by 1995 (about 91 percent), the rate at which companies and start-ups are introduced in the area
decreases. Businesses are still attracted to the area because of its accessibility, proximity to MIT, pool of potential employees, and agglomeration of companies. However, the decrease in the attraction of businesses results, in the long term, in a reduction of the total number of business structures (companies and start-ups), as departure rates outweigh development rates.

Figure 7.8 illustrates some oscillation for business land fraction starting in 2000. This is a result of the constant introduction and departure of firms. In reality, however, this is purely turnover, as old companies leave the area, but new firms join, taking over the space consumed by the previous firm. However, starting in 2015, the fraction of land for business slightly starts to decrease, as the number of firms leaving the area is higher than that of firms coming in.

In the case of the housing sector, the consumption of available land occurs gradually over the 40 year time frame. However, by 2040 about 93 percent of the available land will be already consumed, thus constraining the migration of people into the area. It is not until 2007 when the land availability starts to affect the rate at which houses are built (Figure 7.9). Because land is limited (and land prices increase), the attractiveness for developers decreases gradually, as a result, housing construction rates decrease.

![Figure 7.8 Fraction of Occupied Land](image)
Compared to other system dynamic's models, such as Forrester's *Urban Dynamics* (1969) and Alfeld and Graham (1976), the patterns of growth in the Kendall Square area are somehow different. In the case of Forrester's and Alfeld and Graham, growth does not slow fast enough, though, to prevent overshoot in the population, stock of housing, and stock of business structures. The slowing growth of business structures causes employment opportunities to become scarce, causing population growth through migration to slow. Nevertheless, housing construction, although also influenced by space limitations, does not slow as quickly, due to a bias for housing over business (job-generating) structures. However, excess housing, in turn, creates conditions for decay: the quantity of housing continues to attract a population beyond that which can be supported by the existing business structures. Eventually, an equilibrium is reached in which "the standard of living declines far enough to stop further growth inflow" (Forrester 1969).

In the case of Kendall Square, the decrease in population inflow ("new comers") is not explained by lack of employment opportunities, as the labor force to job ratio is less than one, indicating low unemployment rates, but by the lack of adequate housing units, as housing supply is less than 1 throughout the simulation, evidence of such is presented in Figure 7.10. In fact, the labor force ratio exponentially decreases during the first 5 years of the population as a result of the dramatic growth in jobs.
The houses to household ratio, which ranges from 0.61 to 0.72 throughout the simulation indicates that there are not enough housing units to sustain the population. Therefore, reducing the introduction of new people in the area and potentially reducing the number of people leaving the area. This latter point is due to the fact that, as housing supply is limited, demand for the area increases, increasing rent prices, and therefore, influencing residents’ decisions to move out of the area, assuming socio-economic characteristics of the household do not change. As mentioned in Chapter 6, this is a very simple approach to the very complex relationship between the decision to leave the area and the housing supply.

Similarly, the labor force to job ratio, which is less than 1 over the entire time period, suggests that there are more jobs in the area than labor force, therefore unemployment rates are low. Of course this does not mean that there are excess jobs, as people who work in the area do not necessarily live in Kendall. However, this is a missed opportunity to increase migration rates to the area if housing is limited.

Figure 7.10 Model Indicators for the Initial Simulation

Figure 7.10 suggests that accessibility to the area is one of the major factors contributing to the attractiveness for business and people to locate in the area, though it gradually decreases as more work trips are attracted to the area and transportation infrastructure capacity is not changed. In years 2014 and 2026, approximately, the rate at which accessibility to the area decreases changes.
Taking a closer look at the individual stocks and variables, the decrease in accessibility is a result of two variables: capacity constraints of the transit system and lack of housing supply. These interactions are observed in Figures 7.11 through 7.14.

In the case of residents, accessibility is constant (1) over the entire simulation, as transit capacity limits are not yet reached. For commuters, auto accessibility is zero (0) all throughout, as parking availability constrains the number of trips that can actually occur. From Figure 7.14 it can be seen that the number of auto trips gradually decreases during the entire period reaching the parking capacity. It should be noted that additional parking capacity was allowed assuming workers may rent parking spaces from the residents.

The increase in transit ridership to the Kendall area, as a result of the increase in jobs, reduces the existing capacity of the transit network, hence the reduction in accessibility observed in Figure 7.11. In addition to capacity limitations, the reduction in the growth of housing units reduces the potential of workers moving into the area, hence decreasing accessibility for non-motorized trips, this behaviour can be observed in the bottom pannel of Figure 7.12.

Figure 7.11 Initial simulation output for Kendall Square area accessibility
Figure 7.12 Initial simulation output for the variables influencing Accessibility to Employment
Base Case (1990-2040)

Accessibility to Transit Trips to Kendall

"Ridership to Capacity Ratio (Workers)"

Figure 7.13 Initial simulation output for transit accessibility to Kendall Square
From these figures, it can be concluded that two limiting factors for further growth in the Kendall area are linked to the reduction in transit accessibility and the decrease in housing supply.

Though theoretically excess job opportunities should continuously increase the number of people and companies locating in the area, ultimately, lack of adequate housing decreases residents' decision to locate in the area. As the labor force in the area decreases, business attractiveness to locate in the area decreases. However, the simulation results for Kendall Square suggests that though housing is limited, companies are still attracted to the area as a result of the area's accessibility, though, as described above, it is gradually decreasing. The accessibility to jobs, via transit or non-motorized modes allows for a reduction of the rate at which business development decreases (Figure 7.15). In addition to the limiting factors mentioned above, Figure 7.15 suggests that land availability is another limiting factor for further employment growth.
Figure 7.15 Business Development Multiplier as a result of accessibility, land availability, and labor force.
Taking a closer look at the individual stocks and the variables that influence their behavior provides additional understanding of the complex dynamics that exist. Figure 7.16 illustrates the dynamics observed for the population stock. Particularly, we can observe that the changes in population are basically determined by the migration to the area, rather than the births and deaths, as it was assumed that most of the population locating in the area are young professionals instead of families. As mentioned earlier, the area has experienced a constant increase in the number of people moving into the area ("new comers"), as increases in the number of housing units, job opportunities, and accessibility to the area, increases the attractiveness to move in. However, the model suggests that by 2015, the rate of migration into the area decreases, as housing supply and accessibility decreases (Figure 7.17).

![Figure 7.16 Population Stock inflow and outflow parameters](image-url)
Reading the graph: The graph illustrates 3 values for the 4 graphs. The first value on the y-axis (300 People/Year) is related to the New Comers curve (1, blue curve); 0.7 Dmnl (dimensionless) relates to the Housing Multiplier curve (2, red curve); 2 Dmnl, to the Job Multiplier curve, (3, green curve); and 3 Dmnl relates to the Area Accessibility curve (4, gray curve).
Figure 7.18 presents the inflow and outflow rates for the housing stock. As discussed earlier, the increase in the number of housing units is constant over the entire time period, though construction rate decreases as land becomes scarce. All else being equal, by 2040, the housing stock will increase by 44.8 percent, though housing construction rate decreases from 103 units a year to about 33 units a year. As housing construction slows down and the number of households increase, supply for housing units reduces, hence decreasing the attractiveness to locate in the area and influencing the decision of residents to move out, as the demand for houses increases rent prices.
Figure 7.19 illustrates the total number of business structures at Kendall Square, which aggregates the number of companies and start-ups at a given point in time. From this graph we can observe that the number of start-ups in the area sharply increases during the first 8 years from the original 45 firms to about 85 firms. On the other hand, between 2000 and 2010, the number of start-ups begins to decrease. At the end of the simulation, there are fewer firms (approximately 33) than the initial number of start-ups in 1990. In the case of companies, the increase in the number of this type of firms is constant over the entire period, as the number of firms coming in and departing the area is the same. The low departure rate of this type of firms is due in part to the assumption that these companies cannot relocate to other areas as easily as the more “flexible”, “mobile” start-ups. By 2040, it is estimated that a total of 136 companies will be located in the Kendall Square, an increase of about 19 percent of the initial value.

Our model coincides with some reports which state that by 2011 more than 150 firms were located in the Kendall Square area (Cambridge Community Development Department 2011; Peralta-Quirós 2013), while the model estimates 160 for that year.
The decrease in the number of firms is basically a result of the decrease in land availability and decrease in general accessibility experienced approximately by 2015. It should be noted that although accessibility is decreasing, the area is still accessible; hence business will still be attracted (at a lower rate) to the area.

Figure 7.20 presents the number of transit trips for both workers and residents during the morning period. As it can be observed the network’s capacity is not reached for either group, though the rate at which new riders are introduced into the transit system for trips to the Kendall station starts to decrease around 2015 as attractiveness of transit decreases. By 2040, transit trips to Kendall Square occupy about 95 percent of the system capacity. For the residents, the excess capacity definitely represents an attractive factor for people to locate in the area.

From this model it can be concluded that growth, stagnation, and/or decay are created endogenously despite some simplicity in the model and the high level of spatial aggregation. The analysis suggests that, if the area continues with the same policies and behaviors observed during
the first 20 years, the area will experience a decline in the number of firms and thus, a decrease in the total jobs (Figure 7.19). In addition, though the population in the area exhibits continuous growth, the rate of increase starts to decrease particularly as housing supply becomes limited; hence, discouraging further growth in the area.

As discussed in previous chapters, a combination of parking, zoning, operational infrastructure changes, and urban design policies could encourage development around the area. During the past years, commercial development has favored residential development, but the case of Kendall Square demonstrates that, on the long run, the creation of jobs do not take care of the problem. In the end, for Kendall Square to reap the benefits that greater employment density around transit brings, the city needs to encourage residential development near the commercial development around the station. Failing to take advantage of rail through more intense land development around the Kendall/MIT T-stop is a significant missed opportunity to increase ridership and to make the most of costly transit investments.

7.3. Sensitivity Analysis and Policy Scenarios

Sensitivity analysis can be defined as the study of model responses to some changes in the model parameters. Usually, the main purpose of this analysis is to identify key parameters which significantly affect the model behavior or the variables which could be perceived as controversial, by testing the impact of such parameters.

There are three major sensitivities in System Dynamics models: numerical, behavioral, and policy sensitivity (Haghani, Lee, and Byun 2003):

- **Numerical Sensitivity** is the degree of change in the numerical values of computation results in simulation when a parameter or a structure changes.

- **Behavioral Sensitivity**, which is specific to the dynamic simulation, refers to the degree to which the model behavior changes when the parameter values, typically constant value including table function values, are changed\(^\text{12}\).

\(^{12}\) As Haghani (2003) points out, generally the behavior of system dynamics models tend to be rather insensitive to the acceptable range of changes in parameter values. Here, the model behavior means the patterns of change of shape of graphs. Therefore, insensitiveness to parameter changes doesn’t mean that the model produces the same numerical values despite the parameters changes. Instead, the numerical values are produced differently, but the behavioral pattern is the same.
• Policy Sensitivity is used to evaluate how the model generates different outputs based on reasonable policy options which are usually represented by the parameter values for the associated policy variable\(^ {13}\).

In the following analysis, numerical and behavioral sensitivities for some parameter value changes are analyzed. In addition, policy options are tested to evaluate whether and how the model is sensitive to these policy variables. The analysis is focused on how the model produces different outputs for various variables when parameters of each policy variable are changed, while other conditions are kept constant.

An important advantage of the proposed model is that it can be used as a policy analysis tool, since it generates outputs over all time periods for any variable. Contrary to parameters, policy variables can be controlled by political decisions. Most of the parameters are not controllable however, such as birth rate. Policy impact analysis in system dynamics model is different from other impact analysis in that the periodic impact is identified through the dynamic process.

Several variables in the model were examined to further understand the relationship and effects on other components of the model. The following policies were tested:

1. **Proximity to MIT (P1)** – a value of zero if MIT would not be located near the Kendall Square area.
2. **Infrastructure Changes (P2)** – This analysis examines the effect of changes in the transport infrastructure on the general attractiveness of Kendall Square if they are introduced in 2015. The following scenarios will be tested:
   - Scenario 1: Increase in parking supply
   - Scenario 2: Transit capacity increases (increase in service frequency, the number of cars per train, seating capacity, etc.)
   - Scenario 3: Increase in both parking and transit capacities
3. **Employment Incentive (P3)** – This policy introduces a government program which incentivizes the creation of 5,000 jobs in 2015.
   - Scenario 1: Increase in the number of jobs
   - Scenario 2: Increase in the number of jobs plus an increase in transit capacity

\(^ {13}\) For the later sensitivity test, if a model behavior is very sensitive to reasonable ranges of options, it cannot help to assess the merits of competing policies, and it is useless as a policy analysis tool.
4. **Metropolitan Population Growth (P4)** – This analysis will examine the effects of growth in the metropolitan population on the general attractiveness of the area.

   *Scenario 1:* Increase in the metropolitan population
   *Scenario 2:* Increase in the metropolitan population and increase in the number of jobs

5. **Housing Infrastructure (P5)** – This policy analyzes the effect of residential development on the attractiveness of the area. It will test the following scenarios:

   *Scenario 1:* Housing program is introduced in 2015 which increases the number of housing units, hence increasing housing density
   *Scenario 2:* Scenario #1 plus the increase in transit service capacity
   *Scenario 3:* Scenario #1 plus an increase in the number of jobs

Tables with numerical results for all these policies, as well as for the base case, are included in the Appendix.

*Policy #1*

For example, if MIT would not be located near the Kendall Square area, the initial attractiveness to create jobs in the area would be substantially lower than the base case (about half during the entire analysis). However, this variable follows a similar behavior during the first 20-25 years as the base case. The slow introduction of firms in the area increases the attractiveness for other companies to locate in the area, hence the increase in observed attractiveness. As businesses are attracted to the area at a lower rate, land is not consumed as fast as the initial simulation, thus allowing for the attractiveness of the area to stay constant on the long run compared to the base case (Figure 7.21).
On the other hand, when MIT is not in close proximity, the incentive for small businesses (start-ups) to locate in the area and take advantage of the knowledge spillover and pool of potential employees offered by the Institution obviously reduces; evidence of this is presented in figure 7.22.
Since MIT is the highest source of employment in the area, the decrease in business structures coupled with the absence of MIT, substantially increases unemployment rates in the area though labor force to job ratio is still below 1. In addition to higher unemployment rates, the absence of MIT in the area results in lower population levels (Figure 7.23). This decrease is natural as a portion of the current population living in the Kendall Square study area is related to the MIT campus. For example, students take into consideration various factors when deciding where to live during their college years. In most cases, proximity to the Institution outweighs any other attractor that the area may offer (e.g. accessibility to transit).

![Population Graph](image)

**Figure 7.23 Policy Analysis: Effect of Proximity to MIT on Population Stock**

**Policy #2**

As mentioned, accessibility to the area is one of the key drivers of growth observed during the last 20 years. Though the area is still accessible, accessibility is gradually decreasing and by year 2015, the decreasing rate increases (Figure 7.11). Therefore, we decided to test for a second policy that analyzes the effect of changes in transportation infrastructure. Three scenarios are tested; one which increases the available parking supply, a second scenario which increases transit capacities in 2015, and a third scenario which combines the previous two scenarios.
All else being equal, if parking supply is increased in 2015 by introducing 5,000 additional spaces (Scenario #1); the attractiveness of the area would increase as accessibility to employees increases (Figure 7.24). The spike observed in 2015 is the result of the introduction of the parking spaces. As it can be observed, though accessibility increases during that year, it gradually decreases as more auto trips are made and parking becomes limited. Even though there would be a substantial environmental cost associated with the increase in parking supply, the increase in accessibility results, in the short run, in the attractiveness of companies to locate in the area (Figure 7.26) and thus for the population to increase (Figure 7.25). However, as accessibility decreases, and as a result of the lack of land available by the end of 2040, the total number of business structures in the Kendall Square area is approximately 0.75 percent below the base case, though total jobs is 0.7 percent above. On the other hand, an increase in auto accessibility reduces the congestion on other transit network (e.g. buses). The relief in congestion is captured in the number of transit trips that are transferred from transit to other transit networks. The increase in auto accessibility results in an increase of 15.11 percent in the total number of auto trips to Kendall Square and reduces transit trips to the area by 3.24 percent at the end of 2040.

In order to capture the negative externalities of an increase in parking, it would be ideal to include an environmental sub-model to capture the effects of increases in auto trips in the total emissions levels. The inclusion of this type of sub-model, in addition to further developments to the transportation sub-model to incorporate other transit infrastructures, would allow for more in-depth, long-term analysis of the compounded effects of this type of policy, as it is clear that benefits from increases in parking supply are accompanied by negative externalities such as consumption of urban space, pollution, and increase in travel times.

The second scenario for the infrastructure policy tested for an increase in service capacity, either by increasing transit frequencies, increasing the number of cars per train, the seating capacity per car or a combination of. From the simulation, on the long run, changes in transit capacity have a higher impact on the attractiveness of the area (Figure 7.24). As mentioned, the spike observed in year 2015 results from the introduction of parking spaces. However, the increase in transit capacity has little or no effect on the increase of total population, as the population only increases 1.55 percent by 2040 compared to the base case. By 2040, the increase in service capacity results in a 24.6 percent increase in transit trips to the area and reliefs congestion on other transit networks (Figure 7.28).
The third scenario looked at the effects of combining both of the scenarios discussed above. The patterns or shapes of the graphs are similar to the other two scenarios: an increase in accessibility, for both auto and transit trips, translates into an increase in the attractiveness of Kendall Square, and thus an increase in the number of jobs and total population, though the increase in these are not substantial; less than 2 percent for both parameters. (See gray curve on Figures 7.24 through 7.27).

Figure 7.24 Policy Analysis: Effect of infrastructure changes on Kendall Square's attractiveness
Population

Time (Year)


Population : Base Case (1990-2040)
Population : P2- Scenario #1 (Parking Increase)
Population : P2- Scenario #2 (Increase in Transit Capacity)
Population : P2- Scenario #3 (#Scenario #1 and #2)

Figure 7.25 Policy Analysis: Effects of infrastructure changes to Population Stock

Total Business Structures

Time (Year)


Total Business Structures : Base Case (1990-2040)
Total Business Structures : P2- Scenario #1 (Parking Increase)
Total Business Structures : P2- Scenario #2 (Increase in Transit Capacity)
Total Business Structures : P2- Scenario #3 (#Scenario #1 and #2)

Figure 7.26 Policy Analysis: Effect of infrastructure changes on Total Business Structures in the Kendall Square area
Figure 7.27 Policy Analysis: Effect of number of jobs in the Kendall Square area

Figure 7.28 Policy Analysis: Effect of infrastructure changes on other transit networks
Policy #3

This third policy tested for the effects of job incentives which will increase the number of jobs in the area. Two scenarios were tested; the first scenario introduced 5,000 new jobs in 2015 and the second scenario combined the first with an increase in transit capacity.

This type of policy results in an increase in the number of jobs by the end of 2040 of 8.21 percent and 10.59 percent for the first and second scenario, respectively, though the population only increases by 0.09 and 2.56 percent (Figures 7.29 and 7.30). On the long run, the increase in the number of jobs results in a reduction in the total number of business structures in the area (Figure 7.31), as unemployment rates (labor force to job ratio) decreases even further after 2015, compared to the base case (Figure 7.32); hence decreasing the attractiveness of the area as there is a surplus of jobs compared to the number of workers in the area.

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**Figure 7.29 Policy Analysis: Effects of employment incentive on the number of Jobs**
**Figure 7.30 Policy Analysis: Effects of employment incentive on the Population**

**Figure 7.31 Policy Analysis: Effects of employment incentive on the Total Business Structures**
Naturally, as the number of job opportunities in the area increases, the number of work trips increases. Since auto accessibility to the area is constrained by the parking supply, the only alternative for workers to come into the area is through transit, walking, or biking. If no changes are made to the transit infrastructure, transit accessibility to the Kendall Square area sharply decreases after 2015. This decrease in transit accessibility outweighs any increase in job attractiveness achieved by the increase in the number of job opportunities (Figures 7.33 and 7.34). Hence, we tested for a second scenario which increased transit capacity. The results for this scenario indicate that transit ridership increases by 40.15 percent (Figure 7.35), allowing for an additional increase in the total number of jobs by the end of 2040 (Figure 7.28).
Figure 7.33 Policy Analysis: Effect of employment incentive on Accessibility to Transit to Kendall Square

Figure 7.34 Policy Analysis: Effect of employment incentive on Attractiveness of Kendall Square
Workers may choose to relocate near Kendall Square since employment opportunities in the Kendall have increased as new jobs are introduced in the area in 2015. The possibility of workers to walk and bike to the area – non-motorized trips increase by 6.6 and 6.2 percent for the first and second scenario respectively by the end of 2040 – further increases the attractiveness of the area. Of course, this is assuming that housing conditions in nearby areas allow for these people to move in. As mentioned, this is another limitation of the model, as it is not considering any increase or decreases in attractiveness in areas near the Kendall Square study area.
Policy #4

The fourth policy tested looked at the effects of changes in an exogenous variable, the number of metropolitan home-based-work trips to Kendall Square area. As more people commute to the Kendall Square area, unemployment rates are expected to increase as competition for the number of jobs available increases. In order to analyze this policy, two scenarios were tested. The first increases the number of commute trips to the area as a result of a 1 percent annual increase. The second scenario combines the first scenario with an increase in the number of jobs (similar to Policy #3).

All else equal, the increase in total number of commute trips results in a decrease in accessibility, which in turn result in a decrease in the total number of firms (business structures) at the end of 2040 (Figure 7.37).
Similar to the other policies, Policy #4 results in minimal changes in the total population (Figure 7.38). For both scenarios, population decreases by 1.2 and 0.76 percent respectively. As discussed earlier, the decrease in the population is a result of the increase in unemployment rates and a decrease in accessibility to the area, in addition to the decrease on housing supply.
Until now, the four policies presented result, on average, in less than +/- 1 percent change in the total population of the area, though the total number of jobs is constantly increasing for the various scenarios (See Appendix). These results support previous claims that increases in job opportunities and/or increases in accessibility, on their own, are not going to allow further growth in the area. Housing availability is a key constrain for this growth to occur as suggested by Figure 7.39, which illustrates the houses to household ratio for the initial simulation and for Policies 1 through 4. As it can be observed, Policy 2 reduces the ratio of housing to households approximately 1.5 percent for the three scenarios, while Policy 3 reduces the ratio by 2.23 percent for the second scenario. Only Policy 4 is able to increase the houses to household ratio, but this is a result of the decrease in the number of households as more people leave the area due to the increase in unemployment rates.
Therefore, Policy 5 analyzes the effects of increasing the housing supply by introducing a housing program which increase the number of housing units by 100 units starting in 2015 (Scenario #1). In addition it tested for two other scenarios which combined the increase in housing supply with an increase in transit capacity (Scenario #2) and with the introduction of new jobs (Scenario #3). This policy results in an increase of about 30 percent in the total number of housing units in the area (Figure 7.40).

![Figure 7.40 Policy Analysis: Effect of housing incentive on Housing Stock](image)

Figure 7.41 suggests then, that all else being equal, an increase in the number of housing units results in an increase of approximately 5.9 percent in the population at the end of 2040, while an increase in transit (Scenario #2) and jobs (Scenario #3) result in 7.8 and 6 percent increase, respectively. As Figure 7.42 illustrates, houses to household ratio substantially increases after 2015 with this type of policy, allowing for population to increase. However, Scenario #2 suggests that after 2030, the area will start to experience a shortage of housing units ratio starts to decrease, as housing construction cannot keep up with the increase in population during the first years after the policy was introduced due to land availability.
On the long run, the increase in housing supply increases the area accessibility, particularly for non-motorized trips, as more people can move in and work in the area (Figure 7.43). An increase in transit capacity (Scenario #2) not only increases even further the accessibility to the area, but also allows for this parameter to stay relatively constant over the time period.

The increase in housing units, coupled with the increase in transit infrastructure results in an increase in the total number of business structures in the area. In fact, this scenario presents the highest increase in firms in the area.

![Population Graph](image)

**Figure 7.41 Policy Analysis: Effect of housing program on Population Stock**
Chapter 7

Houses to Households Ratio

![Graph showing the ratio of houses to households from 1990 to 2040. The x-axis represents time in years (1990 to 2040), and the y-axis represents the ratio. There are four scenarios depicted: Base Case (1990-2040), P5 - Scenario #1 (Housing Program Increase), P5 - Scenario #2 (Scenario #1 and Infrastructure Increase), P5 - Scenario #3 (Scenario #1 and Employment). The graph shows an increasing trend in the ratio for all scenarios.]

Figure 7.42 Policy Analysis: Effect of housing incentive on Houses to Household Ratio

Area Accessibility

![Graph showing the area accessibility from 1990 to 2040. The x-axis represents time in years (1990 to 2040), and the y-axis represents the accessibility level. There are four scenarios depicted: Base Case (1990-2040), P5 - Scenario #1 (Housing Program Increase), P5 - Scenario #2 (Scenario #1 and Infrastructure Increase), P5 - Scenario #3 (Scenario #1 and Employment). The graph shows a decreasing trend in accessibility for all scenarios.]

Figure 7.43 Policy Analysis: Effect of housing program on Area Accessibility
Figure 7.44 Policy Analysis: Effect of housing incentive on Total Business Structures
8. Conclusion

8.1. Summary

In the transportation field, models are developed to serve two main purposes. The first is to help in reaching a better understanding and more insights into the behavior of transport systems. The second is to employ models, mainly for forecasting and/or policy analysis by evaluating different scenarios and testing for key sensitivities which can act as policy levers.

Modeling, while not always producing reliable results or trustworthy information, is the best method available to test the likely contributions of alternative courses of action. Consequently, these techniques have attained a central place in the policy making process. However, these models provide forecasts only for those factors and alternatives which are explicitly included in the inputs and equations contained in the models.

Transportation models are required to provide insight and to enhance the understanding of the complex, long-term intra- and interrelations among the transport system and other related systems like land-use, economic development, and the consequences of any given course of action, in terms of new investment and in terms of new management of the system. The relationship between transport and the economy for instance, is of great interest and importance, but still little understood, and there is much disagreement about the topic. The issue is important because it is frequently claimed that new transport investments are essential to help regenerate towns and cities, even when the mechanisms by which this regeneration will arise are not properly explained.

Many researchers agree that urban economies are "complex" systems, but then do not consider systems models to study and understand the dynamics at play. As a result, the analytical framework tends to be grounded on equilibrium economic techniques, even when it is apparent that the problem is essentially dynamic. Traditional models, such as the four-step demand model which operates in four sequential steps, produce outputs in a deterministic manner, following an iterative procedure used to cycle around until equilibrium is reached. Other models that consider the interaction between land use and transport take this equilibrium approach even further, since they attempt to allocate households and economic activity to each zone in the model, in response to changes in the transport network. These models are not only cumbersome and expensive, but from a systems perspective, they fail to address the central issue: that cities are in a state of constant flux,
given the multiple interactions and feedback structures that exist and the temporal component associated with these interactions (Swanson 2008).

In complex, large-scale systems, such as transport, problems are rooted in the basic structure of the system, so that actions taken to deal with one problem may create difficulties elsewhere (Sterman 2000). Simplistic, step-by-step approaches do not cater to the dynamic interactions that exist between the elements and require more coordinated approaches to examine and solve problems. The transportation network of any given city faces particularly complex policy challenges because it encompasses many modes (air, water, highway, transit, and rail) operated and funded by different agencies, both in the public and private sector. Furthermore, transportation decisions are inextricably linked with economic, environmental, and energy policy concerns. Thus, the system is never in equilibrium, as such equilibrium point is continuously shifting as different components of the system interact. Hence, the need to address the issues of a system dynamic modeling approach.

System Dynamics, a methodology that emerged in the late 1960s with the work of Jay Forrester and his colleagues at MIT, provides a common framework through which transport and other related sectors can be incorporated and modeled. The application, benefits, and limitation of this approach to transportation is well documented in the literature (Abbas and Bell 1994; Armah, Yawson, and Pappoe 2010; Haghani, Lee, and Byun 2003; Hensher 2002; Hernández 2011). Some of the benefits include: (1) a structured framework through which large scale systems can be modeled, analyzed, and tested; (2) the integration of feedback structures instead of the traditional step-by-step/input-output model; (3) the use of available data; and (4) the tracing of the short-term and long-term behavior of a system. This last point not only provides insight into the nature of the problem but also allows for timely adjustments to be made. Additionally, System Dynamics provides rich, common media for communication and understanding between the various parties that have interest in the transportation system.

This analytical approach is an effective aid in identifying and appraising alternatives to change the policy for a future course. The “dynamics” in System Dynamics are the fundamental patterns of change, such as growth, decay, and oscillations. So System Dynamics models are constructed to help us understand why these general patterns occur. However it is important to highlight that they are not constructed to predict the exact value of the system at a specific time in the future. The main objective of these models, which forms the perspective of this thesis, is to understand how and why the dynamic trends of concern are generated and to search those management policies needed to modify or improve the system's emerging trends and its causes.
In the last 20 years, Kendall Square has been transformed into a unique business center. The area has become one of the most rapidly growing employment centers in the Greater Boston Area, attracting a certain type of industries, particularly those pertaining to scientific and educational industries and businesses with synergistic relationships to benefit from the agglomeration and cluster benefits of the area. Given its proximity to the Massachusetts Institute of Technology (MIT), employers in the area are able to benefit from the information, technology, and personnel capabilities offered by the Institute. As a result, Kendall Square is able to offer a unique combination of research facilities and education centers of great value to the scientific industries.

In addition to the agglomeration benefits and employment growth, Kendall Square appears to be highly accessible. According to Peralta-Quirós (2013), the area has average commuting times that are amongst the lowest of all employment centers in the Boston Area and rail travel times are equivalent to those by auto. Since a significant percentage of the home-based work (HBW) trips destined to the Kendall Square area are originated in the Square or in the vicinity of Cambridge, 2000 and 2010 modal splits for the area indicate an increase in the share of transit and non-motorized trips (CTPP 2000, ACS 2010). This trend suggests that some new workers in the Kendall area choosing to live near their work location or in close proximity to transit.

Peralta-Quirós (2013) study concludes that the increase in employment density and the formation of bio-tech and start-up clusters observed in Kendall Square have been directly supported by the transit infrastructure in the Greater Boston area. However, we need to ponder questions such as: is the Red Line the main catalyst for its current conditions? Did the transit investment, coupled with proximity to MIT, availability of space for development, parking policies, amongst other policy measures influence its success? Do excessive parking, congestion, and lack of additional transit capacity threaten its future growth?

As mentioned above, transport systems are complex systems and the interaction between transport and land use is far from intuitive. This thesis main purpose is to provide a holistic view of the dynamics taking place in the Kendall Square area. The System Dynamics model built for Kendall Square attempts to improve our understanding of the patterns of growth and the constraints to growth by obtaining relative measures among variables. This approach illustrates how feedback structures in the system can endogenously generate growth, decay, and stagnation.

In order to apply this approach, the modeling work was divided in three steps: a preliminary, a specified, and a comprehensive analysis. The preliminary analysis consists of understanding the
system and identifying feedback structures, while in the specified analysis, the system is constructed and equations are specified. Finally, in the comprehensive analysis, the simulation results from different scenarios are estimated and compared, and relevant conclusions and policies are established.

The model built for Kendall Square takes into consideration changes within approximately a half-mile radius of the MBTA Red Line station and a time span from 1990 to 2040. The model includes population, employment, housing, and transportation, specifically the availability of parking and the MBTA Red Line service, and other variables which have made the area so attractive to live and do business. However, in reality, the system is subjected to other factors, such as macroeconomic trends, that are not accounted for simplicity, and due to the scope of this thesis. It is to be considered as a first attempt to understand the dynamics and patterns in the area.

The model was validated using reported data for 1990, 2000, and 2010 for the total population, housing stock, number of jobs, and the total number of commuting trips by transit, auto, and non-motorized modes. For 2000, the error term for most of these parameters is less than 10 percent, while it falls to less than 2 percent in year 2010 (Table 7.1). The highest error in 2000 was obtained for the number of jobs, as the model presents an error of 26.4 percent above observed data (assumingly due to the economic crisis of that period), though it reduces to 0.2 percent by the end of 2010. For 2010, the error term for non-motorized trips increased to 15.9 below observed data. The results of the model validation seem to indicate that the model is effective enough to simulate the patterns observed in Kendall, as 2010 errors are less than 2 percent for all but one variable.

It should be noted that ridership to and from the Kendall Square/MIT station, total housing units, population, number of jobs, or any other metric are not intended to generate a prediction, but rather serve as a relative measure that enables the user to analyze the patterns of development over time and the differences among scenarios.

The results for the initial simulation indicate a continuous growth in population, housing stock, and employment opportunities, though land availability for business and housing development slows the rate at which jobs and housing units are created, particularly after 2015. The model outputs suggest that there are more jobs in the area, compared to the labor force, as the labor force to job ratio is less than one, which is one positive attractor for people to locate in the area.

However, we were able to identify two limiting factors for further growth in the area linked to the lack of additional transit accessibility and housing supply. The analysis suggests that, if the area
continues with the same policies and behaviors observed during the first 20 years (i.e. no changes to transportation infrastructure, no changes in allowable densities, building heights, etc.), by 2040, the area will experience a decline in the number of firms and thus, a decrease in the total jobs. The city is considering increasing the permitted density, but unless accompanied by improved transit, it is not clear that the scenario will be successful. Though the population in the area exhibits continuous growth, the rate of increase starts to decrease particularly as housing supply becomes limited.

From the model it was concluded that increasing employment density around transit stations is not likely to take care of continuous growth, even if zoning around stations favors uses other than residential. More explicit strategies to encourage business development in Kendall are necessary; particularly strategies to encourage densities should focus at least as much on residential density as on employment density.

One characteristic of public policy problems is the tendency that decision makers have to attribute undesirable events to exogenous rather than endogenous sources, a tendency usually referred to as a "self-serving bias". By attributing adverse events to exogenous factors, we lack the ability to learn from the environment and improve its behavior. A systems approach can help to design policies aimed to improve decaying cities or to prevent stagnation and decay in urban areas that are still growing. It can be argued that an understanding of the main feedback structure of a system is essential for effective policy design. Failing to account for the feedback structure of the system may result in the failure of the suggested policy. Only when the full feedback structure is considered, is likely that the potential flaws of the policy are revealed.

The constraints to growth and the dynamics observed in the area allowed us to design a set of policy measures and scenarios which were tested and compared. One of the policies tested included changes in the transportation infrastructure by increasing the number of parking spaces and/or increasing transit service capacity. This policy highlights the importance of accessibility, particularly transit, to foster employment growth. As more jobs are located in the area, it is important for the local government to improve transit accessibility since it is correlated to employment density. Other two policies considered the introduction of a number of jobs through a government program and the increase in the metropolitan population (an exogenous variable in the model). These policies were also combined with changes in the transportation infrastructure.
The results for all these policies indicated a small change in the total population, on average, less than 1 percent; though the total number of jobs is constantly increasing for the various scenarios. These results support previous claims that increases in job opportunities and/or increases in accessibility, on their own, are not going to allow further growth in the area. Housing availability is a key constraint for this growth to occur. Hence a fifth policy was designed to analyze the effects of increasing the housing supply by introducing a housing program. This policy also included two scenarios which analyzed the combined effect of increasing transit capacity and the introduction of new jobs. In the end, the results for this policy indicate a higher percentage increase in the total population, particularly when transit capacity is increased.

The analysis further suggests that, in the long run, the increase in housing supply increases the area accessibility, particularly for non-motorized trips, as more people can move in and work in the area. In the end, the increase in housing units, coupled with the increase in transit infrastructure results in the highest percentage increase in the total number of business structures in the area.

The System Dynamics model for Kendall Square demonstrates that, in the long run, the creation of jobs do not, by itself, solve the problem. For Kendall Square to reap the benefits that greater employment density around transit brings, the city needs to encourage residential development near the commercial development around the station in addition to increasing transit capacity. Failing to take advantage of rail through more intense land development around the Kendall/MIT T-stop is a significant missed opportunity to increase ridership and to make the most of costly transit investments.

8.2. Research Limitation

Undoubtedly, the Red Line is not the only transit infrastructure that will capture transit users and affect the attractiveness of the area. In its current state, the model is not able to capture the effects of those trips that are not captured by the current system, including auto and transit. The model transfers those "unsatisfied" trips to other transit links, but fails to include the effects of congestion at those links on the attractiveness of the area. It assumes that the system can capture those trips and that it has no effects on the attractiveness of the area, since attractiveness is only affected by the ridership to capacity ratio for transit and by the auto to parking space ratio for auto trips.

Including these effects on the general attractiveness of the area not only would affect employment generation but also immigration to the area. In the case of ridership on the Red Line, as capacity
limits are reached, accessibility to and from the area decreases, decreasing the generation of job and immigration of people. In addition, if we were able to capture conditions on those other links, we would be able to understand the compounded effects of transit changes on the entire network. Making operational changes or expansions to other transit services, for example, by changing frequencies of bus lines running through Kendall Square, including a completely new bus route or introducing circumferential service orthogonal to the Red Line, would undoubtedly affect the current dynamics in the area. Some of these changes may be less expensive and quicker to implement than making longer range changes to the Red Line and undoubtedly, they will alleviate congestion on the rail network.

Despite some of the limitations of the model, we argue that a system dynamics model can greatly aid the policymaking process. System Dynamics models help policymakers learn about the environment and the sources of policy resistance, build learning environments for experimentation, overcome overconfidence, and develop shared understanding among stakeholders. For all these reasons, we believe that this type of approach should be incorporated into policymaking processes related to transportation planning.

8.3. Further Research

The work presented throughout this thesis demonstrated how a system's approach can yield accessible, insightful lessons for policy making. However, additional work can be done to improve the proposed model. Some of the suggestions include the introduction of spatial urban dynamics, additional transportation networks, regional and economic conditions, socio-economic characteristics of the population, and the development of an environmental sub-model.

8.3.1 Spatial Urban Dynamics

In 2004, Peter Sanders introduced the concept of spatial urban dynamics which divides the city in zones. According to Sanders, this represented the reality in a more accurate way, because it includes the zones in a city as individual, endogenously driven system elements that communicate with their environment. Sanders’ explains various reasons to disaggregate the area, which include:

- Aggregation does not justify the settlement patterns observed in reality while aggregation omits the possibility that the zones in a city could have different characteristics (mixture of population, housing, and business) and therefore different functions in a city.
It allows for the introduction of competition between zones.

Allows for a better representation of the behavior of individuals in an urban system, because individuals relocate over relatively short distances (within the city). As Sanders explains, the social environment of a person allows him or her to observe opportunities within the city (zones) sooner than in the surrounding environment. In other words, if an area has higher perceived attractiveness, this will be observed sooner by individuals who live closer to this area.

### 8.3.2 Transportation Network

The model developed for this thesis does not include the complete transportation network for the area, nor the costs and times of travel. Though it indirectly affects mode share, as users are transferred from one mode to the other as capacities are reached (auto and transit), the way it is structured does not allow for mode shares to change. It would be ideal to introduce stocks to represent mode shares for buses, transit, walking, biking, and auto trips taking into account network conditions and logit parameters.

Following the idea of dividing the city into zones, links would be needed to connect all such zones, imitating the transportation networks. Such an approach was used by John Swanson in his Urban Dynamic Model (UDM), so that the network provided access within and between the zones, thus affecting the zone’s attractiveness in several ways:

- **Transport cost and times** – A decrease in transportation costs and times will tend to increase the range of employment opportunities available to the resident workforce, making it easier for them to get to employment centers and therefore increasing the attractiveness as a place to live.

- **Stimulation for growth** – The reduction of the traveling times and costs increases the accessible workforce available for employers to recruit from; as recruitment eases, economic activity increase.

- **Accessibility** – As the pool of accessible business increases, the location’s attractiveness will increase and in turn attract more business, as long as land is available.
Figure 8.1 Left: the development of spatial dimensions in Urban Dynamics (Sanders and Sanders 20004); right: the hypothetical town (Swanson 2008)

This type of model will use traditional logit models to handle mode and route choice, however, the main difference between traditional models and this approach is that it is used within a dynamic framework in which explicit recognition is made of the time needed for people to adapt their behavior. Following the model used by Swanson, Figure 8.2 illustrates how mode choice is handled via a fairly standard goal-seeking mechanism. The “bus mode share” stock is an array of bus mode shares for each origin-destination pair in the model, while the “network conditions” is short-hand for arrays of travel cost and times for each available mode for each origin-destination pair. Given a set of mode-choice parameters the target mode shares can be calculated reflecting current instantaneous network conditions, while the goal-seeking structure generates the actual mode share by tracking the target (Swanson 2008).

Figure 8.2 Example of Mode Share Stock
A more developed transportation network will allow us to model an additional accessibility that may be obtained from projects such as the Grand Junction, which will connect North Station to Kendall Square, and the Urban Ring Transit Line.

8.3.3 Other sub-models, parameters, and model suggestions

- **Migration Sub-model** – This sub-model will define the net migration of the population as a function of socioeconomic factors for different population groups. Generally, migration rates reflect the job market, housing, traffic, and socio-economic conditions of the population (e.g. income levels), and other conditions related to the area (e.g. crime rates, air quality, etc.). Historical migration trends and the relationship between these factors and their effect on migration should be further analyzed and introduced in the model. It might be necessary to disaggregate the population into different groups or "cohorts", since the reasons to move in or out of an area for people over 65 years might be very different to those for younger population groups. The division of the population into different cohorts will also allow for us to make a distinction between the population living in the area because of their relationship to MIT (e.g. graduate community) and all others.

- **National and Regional Economic Parameters** – National and regional gross domestic product (GDP), unemployment rates, and other macroeconomic parameters that capture economic conditions in the Greater Boston area, as well as in the entire country should be incorporated. These will capture previous financial crisis experienced in the U.S. and changes in the socio-economic conditions of the population.

- **Environmental Sub-model** – This sub-model could capture total emission levels in the area as a result of the number of auto trips in the area. In addition, it could capture the negative externalities of increasing parking supply and its effect on the attractiveness of the area.

8.4. Closing Remarks

Following the traditional transportation modeling techniques, one cannot simultaneously obtain the behaviors of multiple metrics over time by endogenously considering all pertinent variables in a complex system as policies are being implemented. Using alternative modeling paradigms, one might be able to get a relationship between two variables, as long as both variables (e.g. congestion levels and changes in behavior among different modes of transportation) are known to have a
certain relationship over time. However, if one understands that transportation, land use, the environment, the economy, etc. work as a system, then the premise is that system behaviors are determined by a system structure. In a two-variable relationship modeling paradigm, the effect of one variable's action on another only represents a partial effect of that variable in a complex system, in which multiple variables actually exert effects on this variable. Therefore, it is hard to evaluate the concurrent dynamic impacts of implementing a given policy on multiple variables over time in this complicated system. An approach such as system dynamics can overcome this problem.

As part of this framework, policy makers and practitioners can identify loops that are responsible for travel demand and mass transit supply dynamics, as well as economic and population growth. By observing the interactions of multiple feedback loops using this approach, not only can they identify fundamental interactions, but they can also see that the consequences of their policies and decisions are separated from them in time and space due to the presence of material and information delays and that these delays affect the outcomes of the system. Understanding these dynamics will allow policy makers to identify critical paths, assist in identifying key performance metrics of the designed system accordingly and formulate appropriate responses. Furthermore, they will not be confounded by certain counter-intuitive or policy-resistant system behaviors while implementing policies as they would have already identified structures that determine emerging behaviors.
9. Bibliography


Transportation Research Record: Journal of the Transportation Research Board 1780 (-1): 87–114.


http://books.google.com/books?hl=en&lr=&id=tvWjovjaxQcC&oi=fnd&pg=PA3&dq=making+the+most+of+transit+density,+employment+growth&ots=TpczD26Nck&sig=V1ssXcdzweD3yj0F73EC06UjiRw.


Appendix A - Model Equations

(001) Accessibility for Residents = Attractiveness of Transit Access from Kendall
Units: Dmnl

(002) Accessibility to Auto Trips to Kendall = WITH LOOKUP (Auto Trips to Parking Ratio, 
\(((0,0)-(1.5,1.5)),(0.1),(0.4,1),(0.6,1),(0.83,0.98),(0.931,0.908),(0.959,0.65),(1,0))
Units: Dmnl

(003) Accessibility to Employment = Accessibility to Auto Trips to Kendall+Accessibility to Transit Trips to Kendall +Attractiveness of Non-Motorized Trips
Units: Dmnl

(004) Accessibility to Transit Trips to Kendall = WITH LOOKUP (Ridership to Capacity Ratio (Workers),\(((0,0)-(1.5,1.5)),(0.1),(0.4,1),(0.6,1),(0.81),(0.91,0.88),(0.982,0.612),(1,0)\))
Units: Dmnl

(005) Adjustment Rate = 5e-005
Units: 1/Year

(006) Area Accessibility = Accessibility for Residents + Accessibility to Employment
Units: Dmnl

(007) Attractiveness Multiplier = IF THEN ELSE(MIT Proximity=0, Attractiveness of Housing Multiplier*Attractiveness of Job Multiplier*Area Accessibility*0.3, Attractiveness of Housing Multiplier*Attractiveness of Job Multiplier*Area Accessibility*MIT Proximity)
Units: Dmnl

(008) Attractiveness of Housing Multiplier = WITH LOOKUP (Houses to Households Ratio, 
\(((0,0)-(1.2)),(0.5,0.502),(0.55,0.522),(0.6,0.547),(0.65,0.578)\),
\,(0.7,0.62),(0.75,0.66),(0.8,0.71),(0.85,0.77),(0.9,0.83),(0.95,0.91),(1,1)\))
Units: Dmnl

(009) Attractiveness of Job Multiplier = WITH LOOKUP (Labor Force to Job Ratio, \(((0,0)-(2.2)),(0.2),(0.343,1.98),(0.61,1.87),(0.7951.68),(1.003,1.254),(1.125,0.763),(1.37,0.289),(1.58,0.103),(1.99,0.0702)\))
Units: Dmnl

(010) Attractiveness of Non-Motorized Trips = WITH LOOKUP (1+Growth of Housing Stock, 
\(((0,0)-(2.1)),(0.27),(0.281346,0.280702),(0.513761,0.298246),(0.733945)\),
\,(0.324561),(0.862385,0.390351),(1,0.5),(1.0581,0.767544),(1.21101,0.917),(1.43731,0.97807),(1.76758,0.995614),(2,1)\))
Units: Dmnl

(011) Attractiveness of Transit Access from Kendall = WITH LOOKUP (Ridership to Capacity Ratio (Residents),\(((0,0)-(1.5,1.5)),(0.1),(0.4,1),(0.6,1),(0.8,1),(0.904,0.882),(0.982,0.612),(1,0)\))
Units: Dmnl

(012) Auto Mode Share (Workers) = 0.674
Units: Dmnl

(013) Auto Trips (Workers) = Total Work Trips to Attracted to Destination*Auto Mode Share (Workers)
Units: People

(014) Auto Trips Expiration Normal = 0.035
Units: 1/Year

(015) Auto Trips Normal = 0.16
Units: 1/Year

(016) Auto Trips to Kendall (AM PEAK) = INTEG (INTEGER(New Auto Trips-Expired Auto Trips),
Initial Auto Trips)
Units: People
(017) Auto Trips to Parking Ratio = IF THEN ELSE(Auto Trips to Kendall (AM PEAK)/Parking Supply>1, 1, Auto Trips to Kendall (AM PEAK)/Parking Supply)
Units: Dmnl

(018) Birth Rate = 0.0005
Units: 1/Year

(019) Births = Population*Birth Rate
Units: People/Year

(020) Business Departure = Companies*Business Departure Normal
Units: Company/Year

(021) Business Departure Normal = 0.009
Units: 1/Year

(022) Business Development = Companies*Business Development Multiplier*Business Development Normal
Units: Company/Year

(023) Business Development Multiplier = IF THEN ELSE(MIT Proximity=0, Multiplier*Business Land Multiplier*Accessibility to Employment*0.3, Business Labor Force Multiplier*Business Land Multiplier*Accessibility to Employment*MIT Proximity)
Units: Dmnl

(024) Business Development Normal = 0.095
Units: 1/Year

(025) Business Labor Force Multiplier = WITH LOOKUP (Labor Force to Job Ratio, ([((0,0)-(2,2)),(0,0),(0.2,0.25),(0.4,0.35),(0,0.6),(0.8,0.7),(1,1),(1.2,1.34), (1.4,1.6),(1.6,1.8),(1.8,1.95),(2,2)]))
Units: Dmnl

(026) Business Land Fraction = 0.28
Units: Dmnl

(027) Business Land Fraction Occupied = (((Companies*Land Per Business Structure)+(start-Ups*Land Per Start-Up Structure))/Land for Business)
Units: Dmnl

(028) Business Land Multiplier = WITH LOOKUP (Business Land Fraction Occupied, ([((0,0)-(2,2)),(0,0.1,1.15),(0.2,1.3),(0.3,1.4),(0.4,1.45),(0.5,1.4),(0.6,1.3),(0.7,0.9), (0.8,0.5),(0.9,0.25),(1,0)]))
Units: Dmnl

(029) Companies = INTEG (INTEGER(Business Development-Business Departure), Initial Companies)
Units: Company

(030) Construction Policy = 0
Units: Dmnl

(031) "Crowding Effects (Residents)" = WITH LOOKUP (Ridership to Capacity Ratio (Residents), [((0,0),(0,0),(0,0.153,0.00132),(0.333,0.00526),(0.517,0.01053),(0.700,0.0184),(0.881, 0.1184),(0.954,0.298),(0.985,0.605),(1,1)]))
Units: Dmnl

(032) Crowding Effects (Workers) = WITH LOOKUP (Ridership to Capacity Ratio (Workers), [((0,0),(0,0),(0,0.153,0.00132),(0.333,0.00526),(0.517,0.01053),(0.700,0.0184), (0.881,0.1184),(0.954,0.298),(0.985,0.605),(1,1)]))
Units: Dmnl

(033) Death Rate = 0.0003
Units: 1/Year
(034) Deaths = Population*Death Rate  
Units: People/Year  
(035) Effect of Congestion (Workers) = WITH LOOKUP (Auto Trips to Parking Ratio,  
\[([[(0,0)-(1,1)],(0,0),(0.153,0.00132),(0.333,0.00877),(0.486,0.0219),(0.813,0.0614),
  (0.963,0.316),(1,1)])\])  
Units: Dmnl  
(036) Effect of Employment = WITH LOOKUP (Labor Force to Job Ratio,\([[(0,0)-(3,3)],(0,0.085),
  (0.489,0.101),(1.055,0.207),(1.431,0.652),(1.532,0.724),(1.611.166),(1.722.066),(1.862.99)]])\)  
Units: Dmnl  
(037) Effect of Housing = WITH LOOKUP (Houses to Households Ratio,\([[(0,0)-(5,1)],(0,0.1),
  (0.2,0.75),(0.4,0.5),(0.55,0.35),(0.8,0.2),(1,0.1),(1.2,0.05),(2,0.009),(3,0.005),(4,0.001),(5,0)]\))  
Units: Dmnl  
(038) Employment Incentive = 0  
Units: Dmnl  
(039) Equilibrium Housing = Population/Household Size  
Units: House  
(040) Expired Auto Trips = \(\max(0,(Auto \text{ Trips to Kendall (AM PEAK)}-Parking \text{ Supply})*Auto \text{ Trips Expiration Normal}*\text{Effect of Congestion (Workers)})\)  
Units: People/Year  
(041) Expired NM = Non-Motorized Trips*NM Trips Expiration Normal  
Units: People/Year  
(042) FINAL TIME = 2040  
Units: Year  
(043) Fraction of Cambridge Residents Working in Cambridge = 0.49  
Units: Dmnl  
(044) Fraction of HBW trips to Kendall = 0.25  
Units: Dmnl  
(045) Fraction of Red Line Transit Trips = 0.548  
Units: Dmnl  
(046) Fraction of Transfer from Transit to NM = 0.1  
Units: Dmnl  
(047) Fraction of Transfers from Transit to Auto = 0.25  
Units: Dmnl  
(048) Fraction of Transfers from Transit to Transit = 0.65  
Units: Dmnl  
(049) Frequency = 9+STEP("Operational Changes (Frequency)",2015)  
Units: Train/Hour  
(050) Growth of Housing Stock = (Housing Construction*Year Adjustment/Houses)  
Units: Dmnl  
(051) House Land Fraction Occupied = min(1, (Land Per Housing*(Houses/Housing Density))/Land for House)  
Units: Dmnl  
(052) Household Size = 1.8  
Units: People/House  
(053) Houses = INTEG (INTEGER(Housing Construction-Housing Demolition),Initial Housing)  
Units: House  
(054) Houses Land Fraction = 0.025  
Units: Dmnl
(055) Houses to Households Ratio = Houses/Equilibrium Housing
Units: Dmnl

(056) Housing Construction = Required Housing*Housing Construction Normal*Housing Construction Multiplier+Introduction of Housing Units
Units: House/Year

(057) Housing Construction Multiplier = Housing Land Multiplier
Units: Dmnl

(058) Housing Construction Normal = IF THEN ELSE(Construction Policy=0, 0.025, 0.025 + STEP(-0.025,2015))
Units: 1/Year

(059) Housing Demolition = Houses*Housing Demolition Normal
Units: House/Year

(060) Housing Demolition Normal = 0.0001
Units: 1/Year

(061) Housing Density = 35+STEP(Increase in Density,2015)
Units: Dmnl

(062) Housing Incentive = 0
Units: House/Year

(063) Housing Land Multiplier = WITH LOOKUP (House Land Fraction Occupied, [(0,-0.03), (1.4,2), (0.04), (0.1,0.7), (0.2,1), (0.3,1.25), (0.4,1.45), (0.5,1.5), (0.6,1.5), (0.7,1.4), (0.8,1), (0.9,0.5), (1,0)])
Units: Dmnl

(064) Increase in Density = 0
Units: Dmnl

(065) Initial Auto Trips = 31051
Units: People

(066) Initial Companies = 65
Units: Company

(067) Initial Housing = 4266
Units: House

(068) Initial Population = 12655
Units: People

(069) Initial Ridership (Residents) = 3099
Units: People

(070) Initial Ridership (Workers) = 7588
Units: People

(071) Initial Start-Ups = 45
Units: Company

(072) INITIAL TIME = 1990
Units: Year

(073) Immigration Normal = 0.0045
Units: 1/Year

(074) Introduction of Employment Program = 0+STEP(Employment Incentive,2015)
Units: Jobs

(075) Introduction of Housing Units = 0+STEP(Housing Incentive,2015)
Units: House/Year

(076) Jobs = (Companies*Jobs per Company)+(Start-Ups*Jobs per Start-Up)+MIT Jobs
+Introduction of Employment Program
Units: People
(077) Jobs per Company = 400
Units: People/Company

(078) Jobs per Start-Up = 25
Units: People/Company

(079) Kendall Area = 2.18878e+007/43560
Units: Acres

(080) Labor Force = Fraction of Cambridge Residents Working in Cambridge*Population+Metropolitan Area HBW Trips *Fraction of HBW trips to Kendall
Units: People

(081) Labor Force to Job Ratio = Labor Force/Jobs
Units: Dmnl

(082) Land for Business = Business Land Fraction*Kendall Area
Units: Acres

(083) Land for House = (Kendall Area*Houses Land Fraction)
Units: Acres

(084) Land Per Business Structure = 50000/43560
Units: Acres/Company

(085) Land Per Housing = 2300/43560
Units: Acres/House

(086) Land Per Start-Up Structure = 12000/43560
Units: Acres/Company

(087) Load Factor = 1.3
Units: Dmnl

(088) Lost Ridership (Residents) = Transit Trips from Kendall (AM PEAK)*Crowding Effects (Residents) *Adjustment Rate
Units: People/Year

(089) Lost Ridership (Workers) = Transit Trips to Kendall (AM PEAK)*Crowding Effects (Workers)*Adjustment Rate
Units: People/Year

(090) Metropolitan Area HBW Trips = 109500+ramp(1095*Metropolitan Population,2015,2040)
Units: People

(091) Metropolitan Population = 0
Units: Dmnl

(092) MIT Jobs = IF THEN ELSE(MIT Proximity=1, 8500, 0 )
Units: People

(093) MIT Proximity = 1
Units: Dmnl

(094) New Auto Trips = (Total Auto Trips (Workers)-Auto Trips to Kendall (AM PEAK))*Accessibility to Auto Trips to Kendall *Auto Trips Normal
Units: People/Year

(095) New Comers = Population*Immigration Normal*(Attractiveness Multiplier)
Units: People/Year

(096) New NM Trips = (NM Trips (Workers)+NM Trips (Residents)- Non-Motorized Trips)*NM Trips Normal
Units: People/Year

(097) New Ridership (Residents) = abs(Transit Trips (Residents)-Transit Trips from Kendall (AM PEAK))*Transit Residents Normal*Transit Multiplier (Residents)
Units: People/Year
New Ridership (Workers) = abs(Total Transit Trips (Workers)-Transit Trips to Kendall (AM PEAK))*Transit Multiplier (Workers)*Transit Workers Normal Units: People/Year

NM Mode Share (Residents) = 0.292 Units: Dmnl

NM Mode Share (Workers) = 0.118 Units: Dmnl

NM Trips (Residents) = NM Mode Share (Residents)*Population Units: People

NM Trips (Workers) = Total Work Trips to Attracted to Destination*NM Mode Share (Workers)+Transfer from Transit to NM Units: People

NM Trips Expiration Normal = 0.2 Units: 1/Year

NM Trips Normal = 0.4 Units: 1/Year

Non-Motorized Trips = INTEG(INTEGER(New NM Trips-Expired NM),5107) Units: People

Number of Vehicles = 10+STEP(Operational Changes (Vehicles),2015) Units: Vehicle/Train

Operational Changes (Frequency) = 0 Units: Train/Hour

Operational Changes (Vehicles) = 0 Units: Vehicle/Train

Outmigration = Outmigration Normal*Population*(0.35*Effect of Employment+0.65*Effect of Housing) Units: People/Year

Outmigration Normal = 0.009 Units: 1/Year

Parking Policy = 0 Units: People

Parking Supply = 24196+STEP(Parking Policy, 2015) Units: People

Passengers Per Vehicle = 55 Units: People/Vehicle

Peak Period Duration = 2 Units: Hour

Population = INTEG(INTEGER(Births+New Comers-Deaths-Outmigration),Initial Population) Units: People

Required Housing = Equilibrium Housing-Houses Units: House

Ridership to Capacity Ratio (Residents) =IF THEN ELSE( Transit Trips from Kendall (AM PEAK)/Transit Capacity (AM PEAK) >1 , 1, Transit Trips from Kendall (AM PEAK)/Transit Capacity (AM PEAK)) Units: Dmnl

Ridership to Capacity Ratio (Workers) = IF THEN ELSE(Transit Trips to Kendall (AM PEAK)/Transit Capacity (AM PEAK) >1, 1, Transit Trips to Kendall (AM PEAK)/Transit Capacity (AM PEAK))
Units: Dmnl

119) SAVEPER = TIME STEP
Units: Year [0,?] 
The frequency with which output is stored.

120) Start-Ups Departure Normal = 0.09
Units: 1/Year

121) Start-Ups Departure = Start-Ups*Start-Ups Departure Normal
Units: Company/Year

122) Start-Ups Development Normal = 0.3
Units: 1/Year

123) Start-Ups Development = Start-Ups*(Business Development Multiplier*Start-Ups Development Normal)
Units: Company/Year

124) Start-Ups = INTEG(INTEGER(Start-Ups Development-Start-Ups Departure),Initial Start-Ups)
Units: Company

125) TIME STEP = 1
Units: Year [0,?]
The time step for the simulation.

126) Total Auto Trips (Workers) = IF THEN ELSE(Transfer from Transit to Auto<0, Auto Trips (Workers), Transfer from Transit to Auto+Auto Trips (Workers))
Units: People

127) Total Business Structures = Companies+Start-Ups
Units: Company

128) Total Transit Trips (Workers) = IF THEN ELSE(Transfer from Auto to Transit Trips (Workers)<0, Transit Trips (Workers),Transfer from Auto to Transit Trips (Workers)+Transit Trips (Workers))
Units: People

129) Total Work Trips to Attracted to Destination = Jobs
Units: People

130) Transfer from Auto to Transit Trips (Workers) = Unsatisfied Auto Trips (Workers)
Units: People

131) Transfer from Transit to Auto = Fraction of Transfers from Transit to Auto*Unserved Transit Trips (Workers)
Units: People

132) Transfer from Transit to NM = Unserved Transit Trips (Workers)*Fraction of Transfer from Transit to NM
Units: People

133) Transfer from Transit to Transit (Other) = Unserved Transit Trips (Workers)*Fraction of Transfers from Transit to Transit
Units: People

134) Transit Capacity (AM PEAK) = Frequency*Number of Vehicles*Passengers Per Vehicle*Peak Period Duration*Load Factor
Units: People

135) Transit Mode Share (Residents) = 0.277
Units: Dmnl

136) Transit Mode Share (Workers) = 0.208
Units: Dmnl

137) Transit Multiplier (Residents) = WITH LOOKUP (Ridership to Capacity Ratio (Residents),
[[0,0)-(1.5,1.5)],(0,1),(0.4,1),(0.6,1),(0.8,1),(0.904,0.882),(0.982,0.612),(1,0)])
Units: Dmnl
Transit Multiplier (Workers) = WITH LOOKUP (Ridership to Capacity Ratio (Workers),

\([0.0, 0.1, 0.2, 0.3, 0.4, 0.6, 0.7, 0.8, 0.85, 0.9, 1.0]\))

Units: Dmnl

Transit Residents Normal = 0.035
Units: 1/Year

Transit Trips (Residents) = Population*Transit Mode Share (Residents)*Fraction of Red Line Transit Trips
Units: People

Transit Trips (Workers) = Transit Mode Share (Workers)*Total Work Trips to Attracted to Destination
Units: People

Transit Trips from Kendall (AM PEAK) = INTEG (INTEGER(New Ridership (Residents)-Lost Ridership (Residents)),Initial Ridership (Residents))
Units: People

Transit Trips to Kendall (AM PEAK) = INTEG (INTEGER(New Ridership (Workers)-Lost Ridership (Workers)),Initial Ridership (Workers))
Units: People

Transit Workers Normal = 0.035
Units: 1/Year

Unsatisfied Auto Trips (Workers) = IF THEN ELSE(Auto Trips (Workers) >Auto Trips to Kendall (AM PEAK), Auto Trips (Workers)-Auto Trips to Kendall (AM PEAK), 0)
Units: People

Unserved Transit Trips (Residents) = IF THEN ELSE(Transit Trips (Residents)<Transit Trips from Kendall (AM PEAK), 0, Transit Trips (Residents)-Transit Trips from Kendall (AM PEAK))
Units: People

Unserved Transit Trips (Workers) = Total Transit Trips (Workers)-Transit Trips to Kendall (AM PEAK)
Units: People

Year Adjustment = 1
Units: Year
Appendix B – Policy Analysis Results

Table B.1 Changes in Population Stock for all policies

<table>
<thead>
<tr>
<th>Year</th>
<th>P1</th>
<th>P2 #1</th>
<th>P2 #2</th>
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Table B.2 Changes in Housing Stock for all policies

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Table B.4 Changes in Transit Trips to Kendall/MIT Stock for all policies

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Table B.5 Changes in Transit Trips from Kendall/MIT Stock for all policies

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## Appendix B

Table B.6 Changes in Non-Motorized Trips Stock for all policies

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Table B.7 Changes in Auto Trips to Kendall Square Stock for all policies

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Table B.8 Changes in Area Accessibility for all policies

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Table B.9 Changes in Houses to Household Ratio for all policies

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