FINDING WAYS OUT OF CONGESTION FOR THE CHICAGO LOOP -- A MICROSCOPIC SIMULATION APPROACH

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Submitted to the Department of Civil and Environmental Engineering and the Department of Urban Studies and Planning in partial fulfillment of the requirements of the degrees of

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Abstract

Over the past two decades, the City of Chicago, as many of its counterparts in the U.S., has experienced a great increase in traffic congestion, which limits regional mobility, induces a huge amount of energy waste and Greenhouse Gas emissions, and impedes economic development. Due to congestion, bus reliability and travel speed has decreased significantly. Since the demand served by the rail system in the Chicago Loop has almost met its capacity during peak hours, and the Loop area concentrates a high percentage of total bus passenger boardings, improving bus Level-of-Service (LOS) in the Loop area is crucial to enhancing passenger mobility in the City of Chicago.

As a promising alternative, bus rapid transit (BRT) may reduce negative impacts of traffic congestion; however the real challenge addressed in this thesis is how to evaluate the impacts of such policies on different stakeholders (i.e., auto-drivers and bus-riders) prior to its implementation and how to inform policy-makers on sound policy decisions.

In order to address the aforementioned problems, this thesis relies on the preparation of a VISSIM microscopic traffic simulation model for the Chicago Loop area, and the utilization of a GIS traffic network, traffic counts, traffic signals and the CTA bus service data. This study proposes three sets of indicators for the purpose of evaluation of the proposed schemes: 1) bus and auto travel speed, 2) bus reliability, and 3) average bus and auto delay time. These performance indicators will serve to compare the current base case to the proposed bus improvement (e.g. BRT) scenarios. Based on the evaluation of several scenarios, this study provides practical recommendations on how to alleviate the impact of traffic congestion on buses in order to improve bus LOS in the Chicago Loop area.

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Chapter 1 Introduction

In the last two decades, as the population and economic growth has continued in many U.S. cities, most of them have faced a tremendous challenge—traffic congestion—brought by increased automobile travel. Given this background, this thesis takes Chicago as an example to demonstrate the importance of improving bus level-of-service (LOS) to reduce the negative impacts of traffic congestion. This thesis examines the different facets of several alternative futures for bus improvements, such as bus rapid transit (BRT), while reviewing the essential elements of success of a BRT system. It includes also a framework to set up and to evaluate potential bus improvement scenarios. This framework includes a set of performance indicators and a microscopic traffic simulation tool, which links planning and operations and enables the evaluation of potential bus improvement scenarios. By preparing and evaluating different bus improvement scenarios using the microsimulation models built for this study, this thesis provides a series of recommendations to improve bus LOS in downtown Chicago.

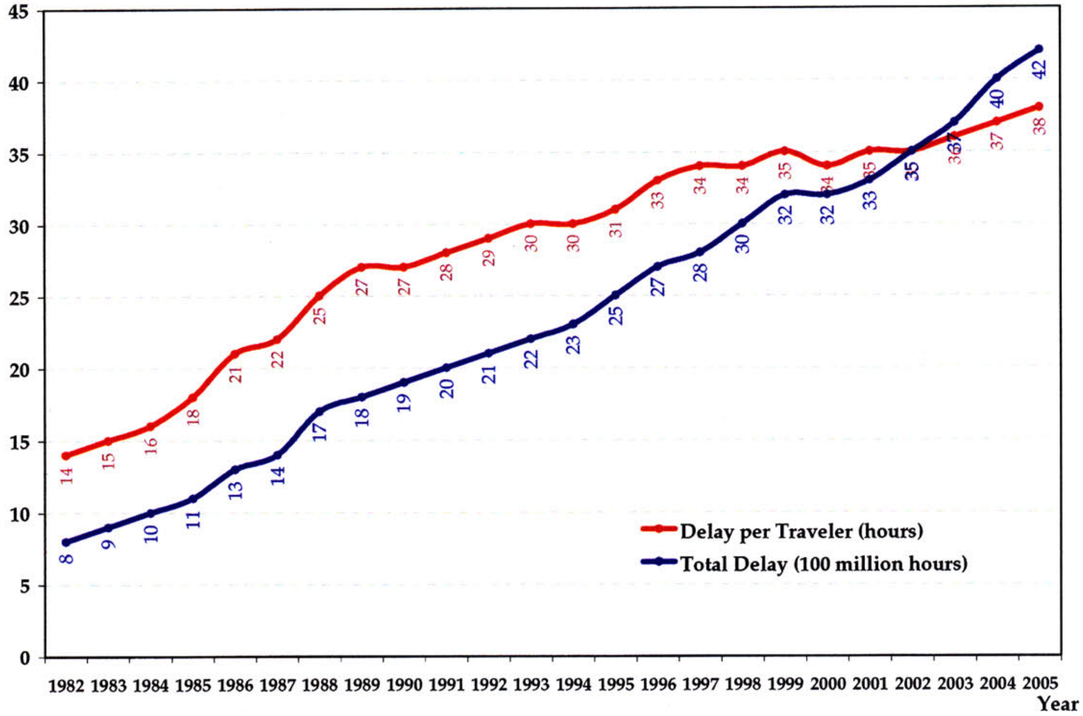
1.1 Research Motivation

As aforementioned, traffic congestion has become a major threat to the efficiency and quality of life in U.S. cities. Travel delay, energy waste, greenhouse gas emissions and the resultant economic losses due to congestion has aroused federal, state and local governments' attention to mobilize every possible resource to relieve congestion. Among those congestion mitigation efforts, public transportation has shown its potential and advantages in saving energy, reducing greenhouse gas emissions and revitalizing urban images. However, in spite of being an important mode of public transportation, buses sitting in traffic jams suffer the same degree of traffic congestion as automobiles do. Thus improving bus level-of-service (LOS) and switching more auto drivers to bus systems is essential to mitigate traffic congestion.

1.1.1 Traffic Congestion in the U.S. Cities

The renowned annual *Urban Mobility Report* by the Texas Transportation Institute (TTI) has aroused peoples' awareness on how severe the congestion problem has been nationwide. The most recent *Urban Mobility Report* (TTI, 2007) indicates that from year 1982 to year 2005, for all the 437 U.S. urban areas studied, the travel delay per traveler has increased from 14 hours to 38 hours annually, and the total delay per year has climbed from 0.8 billion hours to 4.2 billion hours (see Figure 1-1). The importance of these escalating numbers is that they represent very significant losses wasted in congestion.

Figure 1-1 **Individual and Aggregate Annual Travel Delay in the U.S., 1982-2005**



Source: TTI, 2007

1.1.2 Social, Economic and Environmental Costs of Congestion

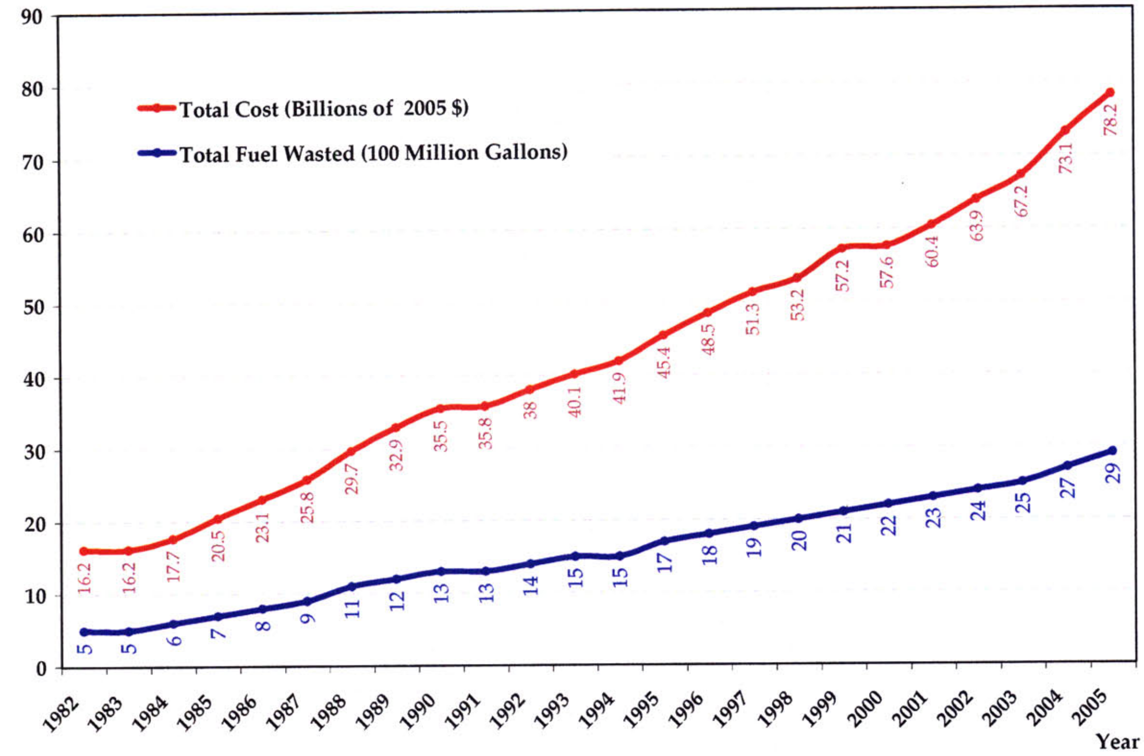
From 1982 to 2005, according to the same report the total costs due to congestion have increased for the 437 U.S. urban areas studied, from 16.2 billion dollars to 78.2 billion dollars (in 2005 $), which equaled 0.63 percent of the U.S. Gross Domestic Product (GDP) in year 2005[1]; and the total fuel wasted has increased from 0.5 billion gallons to 2.9 billion gallons, equivalent to 58 supertankers (see Figure 1-2).

In terms of environmental impacts, among six economic sectors (i.e. electric power industry, transportation, industry, agriculture, commercial and residential), the transportation sector has ranked No.2 in terms of the amount of GHG emissions in Teragrams of CO2 Equivalents (Tg CO_2 Eq.) since 1990 (see Figure 1-3, EPA, 2008). When having a closer look within the transportation sector (Figure 1-4), it can be noticed that passenger cars shared the largest percentage of GHG from year 1990 to year 2006, while bus shared the least portion. The increased travel demand by motor vehicles has imposed increasingly heavier pressures on the environment, especially when they result from sitting hours in traffic jams and generating more GHG emissions.

---

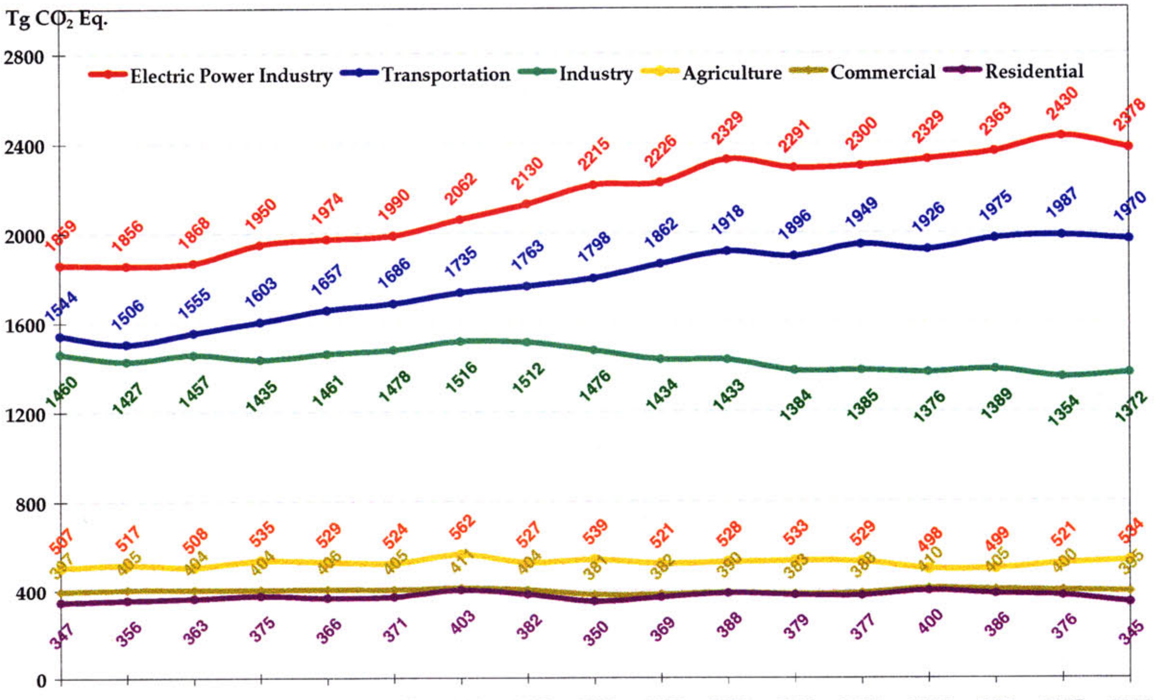
[1] Data is obtained from the National Income and Product Accounts Table 1.1.5 Gross Domestic Product. In year 2005, the U.S. annual GDP was 12421.9 billion dollars. (http://www.bea.gov/national/nipaweb/)

Figure 1-2 **Annual Cost and Fuel Waste Due to Congestion in the U.S., 1982-2005**



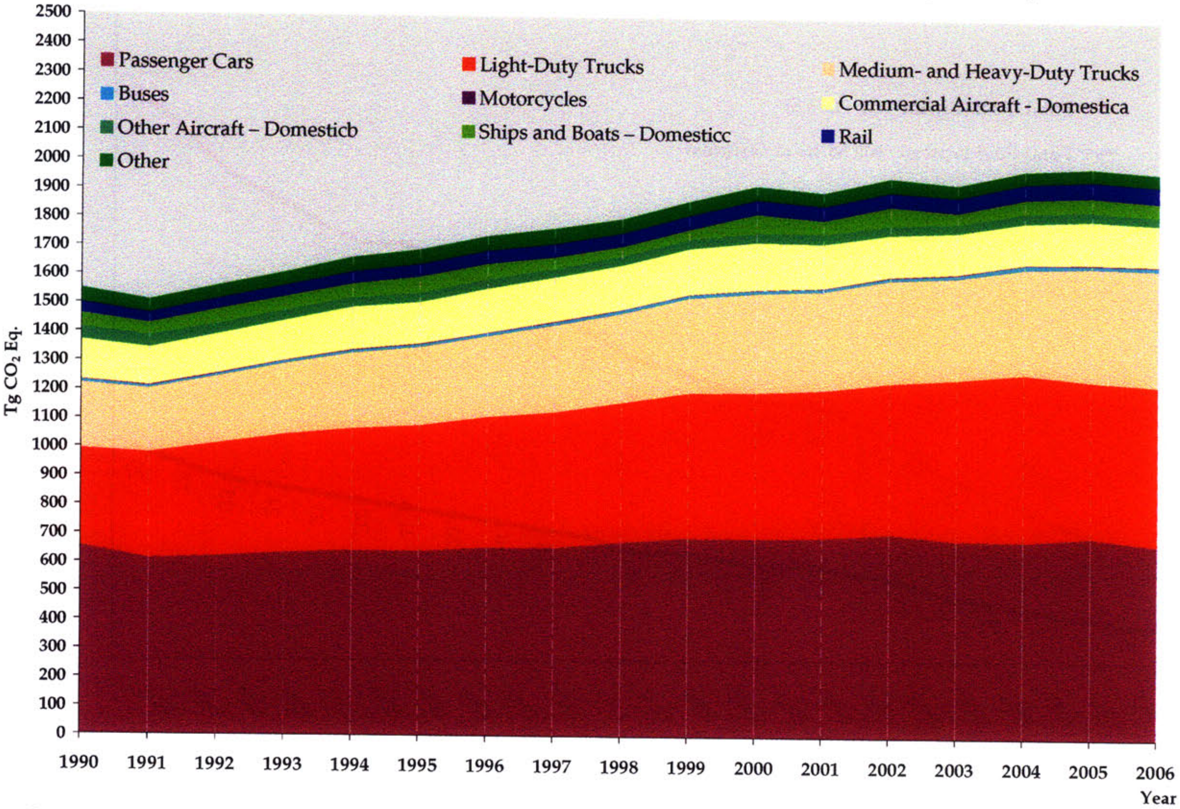
Source: TTI, 2007

Figure 1-3 **U.S. GHG Emissions Allocated to Economic Sectors (Tg CO_2 Eq.)**



Source: U.S. EPA, 2008

Figure 1-4 U.S. Transportation-Related Greenhouse Gas Emissions (Tg CO_2 Eq.)



Source: U.S. EPA, 2008

1.1.3 *Congestion Mitigation and Travel Demand Management (TDM)*

As traffic congestion becomes more severe in a larger percent of U.S. urban areas, for longer portions of each day, provoking higher costs of energy and recourses of the whole society, mitigating congestion by any means becomes imperative. Traffic demand management (TDM), which originated in the 1970s and 1980s, aimed to provide alternatives to single occupancy commuter travel to save energy, improve air quality, and reduce peak period congestion (US DOT FHA Office of Operations, 2004).

There has been a variety of TDM strategies that aim to reduce traffic congestion, such as congestion pricing, commute trip reduction programs (e.g. the Mobility Pass Program at MIT, Block-Schachter & Attanucci, 2009), transit improvements (e.g. BRT), rideshare programs (e.g. HOV lanes), parking management and pricing, fuel pricing, traffic calming programs, car-free programs, vehicle restrictions, and land use and urban growth management strategies (e.g. smart growth) (VTPI, 2008).

Table 1-1 Examples of Travel Demand Strategies, Mechanisms and Impacts

TDM Strategies	Mechanism	Travel Changes
Road/Congestion Pricing	Pricing	Shifts travel time, reduces vehicle travel on a particular roadway.
Distance-based charges	Pricing	Reduces overall vehicle travel.
Transit improvements	Improved transport choice.	Shifts mode, increases transit use.
Rideshare promotion	Improved transport choice.	Increases vehicle occupancy, reduces vehicle trips.
Car sharing	Improved transport choice.	Reduces vehicle ownership and trips.
Flextime	Improved transport choice.	Shifts travel time (when trips occur).
Pedestrian and bicycle improvements	Improved transport choice, facility improvements.	Shifts mode, increases walking and cycling.
Traffic Calming	Roadway redesign.	Reduces traffic speeds, improves pedestrian conditions.
Smart Growth, New Urbanism	More efficient land use, improved travel choices.	Shifts mode, reduces vehicle ownership and trip distances.

Source: VTPI, 2008

Contemporary practices of demand-side management strategies have broadened from facilitating shifts in travel mode, to travel routes and departure times, and from commuting trips to non-commuting trips (ACT, 2004). Intelligent Transportation Systems (ITS) have been intensively applied to support TDM to provide travelers with information and to facilitate them with better travel choices thus improving the efficiency of transportation systems and reducing congestion.

1.1.4 The Role of Public Transportation

Alleviating Traffic Congestion

Among a variety of the congestion relief strategies, public transportation has played an important role in alleviating traffic congestion. In 2005, public transportation in the U.S. saved 429.6 million hours in 14 very large cities, 63.9 million hours in 25 large cities, 14.7 million hours in 30 medium cities, 1.4 million hours 16 small cities, resulting a total of 540.9 million hours all the 437 U.S. cities studied by TTI (2007). Without public transportation, travel delays would have increased 13 percent. Comparing to other operational treatments, such as incident management, access management, HOV priority lanes, ramp metering, and signal coordination, public transportation was the most effective means for reducing traffic congestion (see Table 1-2, TTI 2007).

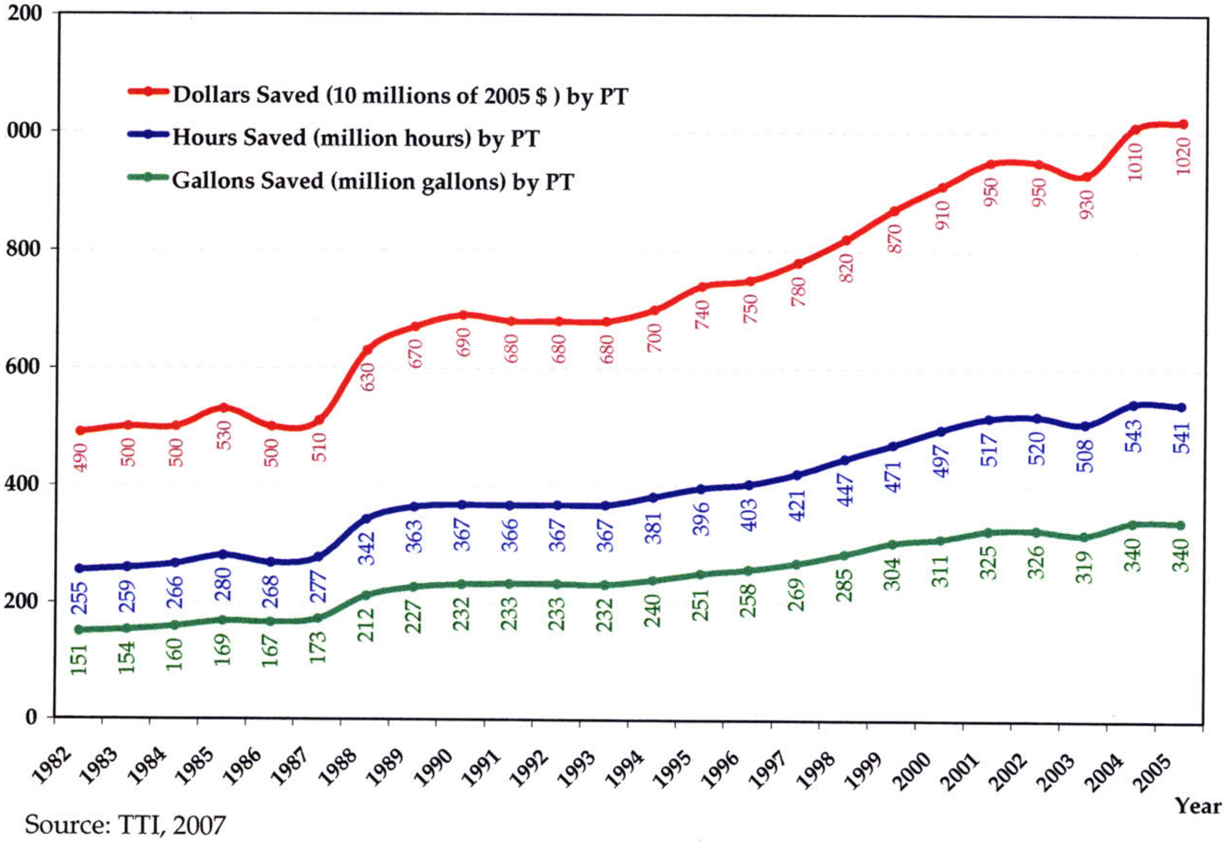
Table 1-2 Comparison of Delay Reduction Effects of Different Treatments, 2005

	Annual Million Hours Saved by Population Group					
	Very Large	Large	Medium	Small	Intensively Studied	All 437
Number of Cities	14	25	30	16	85	437
Savings from						
Public Transportation	429.6	63.9	14.7	1.4	509.6	540.9
Incident Management	96.5	24.1	6	0.2	126.8	129.4
Access Management	38.3	13.7	4.9	0.8	57.7	68.6
High-Occupancy Vehicles	31.8	2.9	0	0	34.7	34.7
Ramp Metering	29.4	9.2	0.1	0	38.7	38.7
Signal Coordination	10.9	3.7	1.8	0.3	16.7	20.7

Source: TTI, 2007

Converting the previously mentioned figures into monetary terms and gasoline consumption, in 1982, public transportation saved the 437 U.S. cities 4.9 billion dollars, and 151 million gallons of gasoline; while in 2005, the number rocketed to 10.2 billion dollars and 340 million gallons of gasoline (see Figure 1-5, TTI, 2007).

Figure 1-5 Temporal, Economic and Energy Savings by PT, 1982-2005



Source: TTI, 2007

Saving Energy and the Environment

The above mentioned 340 million gallons of gasoline savings also imply 3 million metric tons of CO_2 emission reduction attributed to congestion relief by public transportation. On the other hand, it is estimated by APTA that 3,820 million gallons of gasoline and 34 million metric tons of CO_2 emissions have been saved by public transportation due to: 1) travel mode shift from private vehicles to public transportation; 2) travel distance reduction due to destination decision changes related to public transportation (see Table 1-3, APTA, 2008).

Table 1-3 Energy and Emission Benefits from Public Transportation, 2005

Changes in Fuel Use Due to Public Transportation	Total Energy Savings (10^6 Gallons of Gas Equivalent)	CO_2 Emission Reductions (10^6 Metric Tons)
Primary Reduction from Riding Transit as Replacement of Private Vehicles	1,800	16.2
Secondary Reduction due to Reduced Travel Distance Related to Destination Choices	3,400	30.1
Savings to Private Vehicle Drivers because of Congestion Reduction due to Transit	340	3
Fuel Used by Transit	-1,380	-12.3
Total Savings due to Transit	4,160	37

Source: APTA, 2008 (adapted from ICF International, 2008 and SAIC, 2007 Appendix B)

Improving Urban Image and Promoting Sustainable Development

Public transportation often also improves urban image and promotes sustainable development. By improving transit facilities and their surrounding pedestrian environment, planners and designers are able to create a vibrant and livable urban fabric that supports walking, biking and usage of transit.

Figure 1-6 shows several examples of how public transit improvement programs may re-shape urban form and urban image. The first two pictures on the top row are demonstrations of the K-street bus way in Washington D.C. The left one on the bottom is an illustration of Portland Transit Mall, and the right one is a section of the Eugene/Springfield BRT Pilot Corridor (Newlands & Company, Inc, 2009). Improving transit infrastructure and services, especially bus transit facilities, will not only reduce travelers' travel time; but also adds vibrant elements to cities. The message is that cities are not designed for cars, but for people who live there.

Figure 1-6 Urban Design and Public Transit Improvement

Source: Newlands & Company, Inc, 2009[1]

1.1.5 The Need for Improving Bus Level-Of-Service

Albeit public transit has inevitable advantages in alleviating traffic congestion, saving energy consumption and reducing greenhouse gas emissions, there are still obstacles to improving its level-of-service.

From 1995 to 2006, bus served at the national level, the largest amount of both unlinked passenger trips and passenger miles, compared to other public transportation modes such as heavy rail, light rail, and commuter rail (see Figure 1-7 and Figure 1-8).

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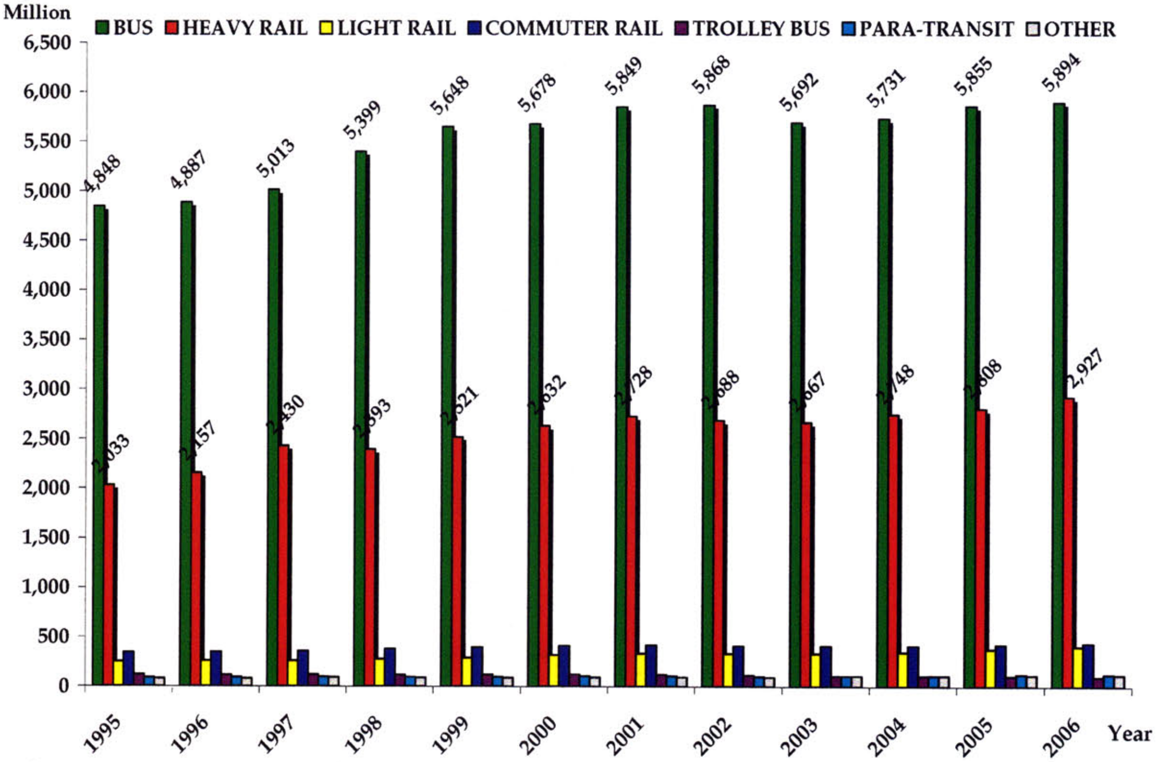
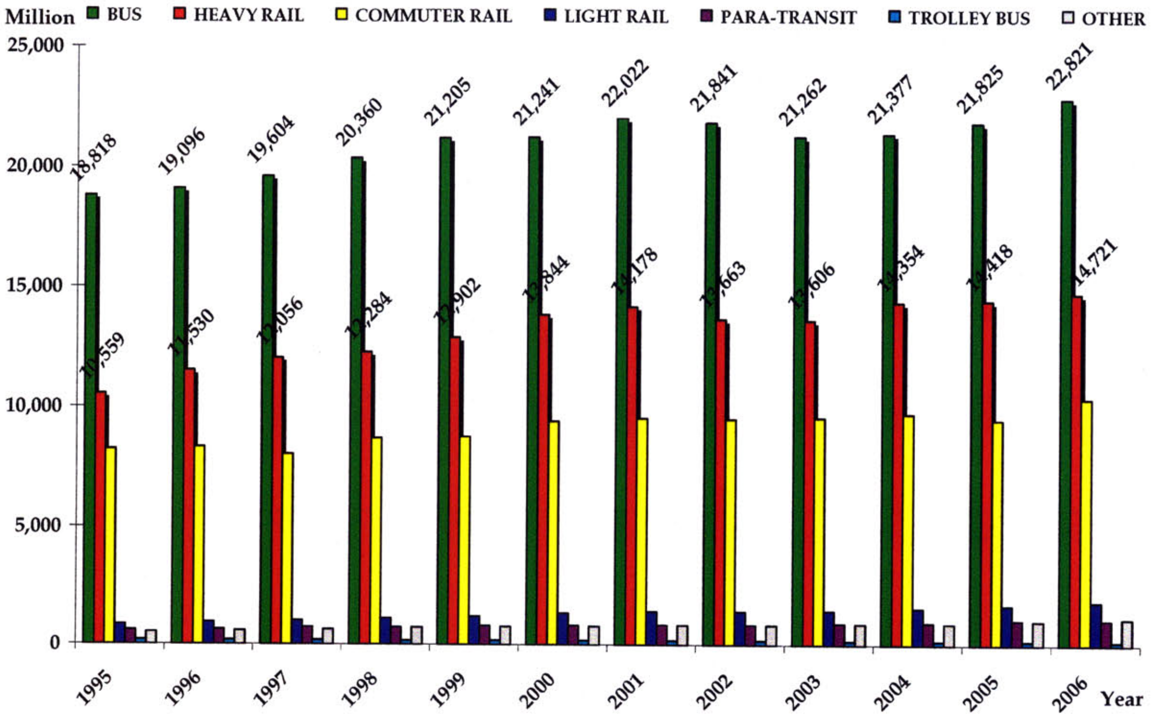
[1] Retrieved January 20, 2009, from http://www.nc3d.com

Figure 1-7 **U.S. Unlinked Passenger Trips (millions) by Mode, 1995-2006**



Source: APTA, 2008

Figure 1-8 **U.S. Passenger Miles (millions) by Mode, 1995-2006**



Source: APTA, 2008

However, as buses often have to suffer the same level of traffic congestion as private motor vehicles on the road, the average vehicle speed for buses nationwide was as slow as 12.6 mile per hour (mph) in 2006. In fact, the bus was ranked by APTA the second slowest mode among all seven public transportation modes (Table 1-4).

Table 1-4 Average Vehicle Speed in Revenue Service by Mode, 2006

Mode	Average Speed (mph)
Trolleybus	7.4
Bus	12.6
Para-transit	14.6
Light Rail	14.7
Heavy Rail	20
Commuter Rail	31.4
Other	31.6
Total	14.7

Source: APTA, 2008

Table 1-5 summarizes bus performances measures for buses running in downtown streets based on observed field surveys by Jacques and Levinson (2000). In this table for buses running on downtown streets in four surveyed U.S. cities—Portland, New York City, Ottawa, and San Antonio— the main indicators are a) bus stop frequency ranging from 5 stops/mi to 10 stops/mi; b) peak 15-minute bus flow rates ranging from 16 to 164 buses/hour; c) bus median dwell time ranging from 18 second to 32 second; and d) bus speeds ranging from 2.6 mile per hour to 12.8 mph (some of which were much slower than the 2006 national average bus speeds).

Table 1-5 Bus Performance on Downtown Streets in Four U.S. Cities

	Fifth Ave. Portland	Sixth Ave. Portland	Second Ave. New York City	Albert St. Ottawa	Commerce St. San Antonio	Market St. San Antonio
Type of Lane	Dual	Dual	Curb	Curb	Curb	Curb
Stops per Mile	10	10	8	5	10	6
Hourly Bus Flow Rates by 15-Min Interval						
Range	76–164	88–112	16–52	100–164	56–100	80–108
Median	136	96	26	132	80	96
Dwell Times by 15-Min Interval (sec)						
Range	10–65	8–55	19–78	15–27	10–32	23–30
Median	29	32	29	18	22	26
Mean C.O.V.	0.52	0.54	0.57	0.59	0.81	0.57
Bus Speeds Compiled by 15-min intervals (mph)						
Mean Speed Range	2.6–4.7	3.7–4.2	4.4–8.0	9.1–12.8	4.2–6.3	6.0–7.0
S.D. Range (mph)	0.5–1.5	0.9–1.5	0.2–2.7	1.3–3.6	0.6–1.5	1.0–2.3

Source: Jacques and Levinson, 2000.

Considering the large amount of passenger trips and passenger miles traveled by bus, and its slow travel speed, improving bus level-of-service becomes crucial. Even a small improvement in bus travel speed, may lead to a very large saving of total passenger travel time. Bus rapid transit (BRT) is a very promising alternative, because it can provide buses with their own right-of-way, and thus reduce bus travel time significantly, together with other service improvements associated to the BRT concept.

1.2 Research Objectives

Given the importance of improving bus transit LOS, this thesis poses two questions: 1) how to evaluate a specific transit improvement program, and 2) how to ensure that improvement plans are feasible and operationally effective before implementation.

1.2.1 Define Appropriate Indicators

In order to answer the first question, three sets of indicators are defined to evaluate the effectiveness and performance of transit improvement programs. These chosen measurements are 1) reliability, 2) travel speed, and 3) travel delay.

Reliability

Reliability of the transit system, specifically for buses, includes running time reliability and dwell time reliability. Running time reliability relies on the ability to maintain a consistently high travel-speed to provide bus riders with consistent travel times. Dwell time reliability represents the ability that bus vehicles to consistently load passengers within a certain relative dwell time per passenger so as to minimize the amount of time spent at bus stops(Diaz et al., 2004).

Travel Speed

Travel speed is a classic reflection of transportation accessibility. We will evaluate both the overall average travel speed of different modes in the defined network, and bus travel time improvement for specific bus corridors such as sections along Michigan Avenue, as well as automobile travel speed changes for different transit improvement scenarios.

Delay Time

Delay time is another indicator measuring the effectiveness of the bus LOS changes. Compared to target travel time, a delay time measurement determines the mean time delay calculated for all vehicles of a defined mode observed on a signal or along several sections. The goal is to compare the delay time of different modes for bus improvement scenarios.

1.2.2 *Develop an Efficient Tool to Link Planning and Operations*

To ensure that the improvement plan provides a feasible and effective solution, we need to develop efficient tools to link planning and operations, which are essential to improving transportation decision-making and the overall effectiveness of transportation systems.

The linkage between planning and operations is important from various aspects. First, to "promote efficient system management and operation" has become one of the seven planning factors that must be considered in the planning process at metropolitan and state levels. Second, given the environmental, community and funding constraints that limit transportation agencies' ability to build new capacity to address the increasing transportation needs and demand, the public requires that new improvements operate at peak efficiency before providing funding to expand physical capacity (US DOT FHA, 2004).

However, traditional planning support systems such as geographic information systems (e.g. ArcGIS, and TransCAD) do not incorporate behavioral aspects and therefore are not capable of predicting reliable estimates of functional and performance changes. Microscopic traffic simulation models, on the contrary, have been developed to address this kind of operational issues.

To this end, this thesis involves the preparation of a microsimulation model to examine the impacts that different scenarios of bus improvements will have to relieve the impact of traffic congestion on the bus system in Chicago to effectively link planning and operations before project implementation.

1.3 Thesis Organization

In the first Chapter, this thesis discusses 1) the background of this research: the growing traffic congestion in the U.S., its negative impacts on the economy, environment and society, and the role of public transportation in alleviating congestion; and 2) the motivation and objectives of this research: to develop an efficient tool capable of an accurate estimate of the feasibility of alternative plans to improve bus level-of-service.

Chapter 2 will focus on a specific U.S. metropolitan area, Chicago, introducing its current traffic congestion severity, its public transportation conditions, and its congestion relief initiatives—including a new BRT plan.

Chapter 3 will discuss generally the concept and characteristics of Bus Rapid Transit (BRT), how to plan a successful BRT system, and how to evaluate the effectiveness of a BRT system.

Chapter 4 will in detail lay out the structure of a microscopic traffic simulation approach, which is very helpful to evaluate current traffic conditions and scenarios of future bus transit improvement. This chapter will first discuss microsimulation in theory and practice, making reference to existing commercial and research software packages that have been developed worldwide, and their application scope. Then it will focus on the preparation of the Chicago Loop microsimulation model, every significant element that composes the model, its underlying mechanisms, and finally the model calibration process.

Chapter 5 describes several bus improvement scenarios, and evaluates the scenarios against the base case by doing sensitivity analyses.

Chapter 6 concludes the analyses, reviews the advantages and disadvantages of the microsimulation model for the purposes of the BRT in downtown Chicago, and explores potential future research and applications.

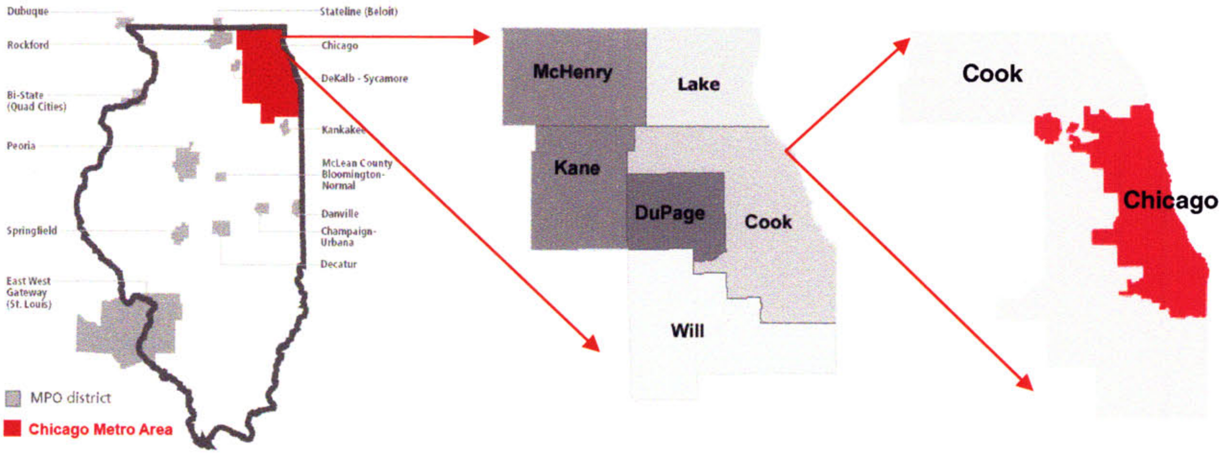
Chapter 2 Case Study: Chicago

In this chapter, this thesis examines Chicago as a specific example to demonstrate the motivation and the potential of improving public transit services. The transit system in Chicago is the second largest system in the U.S. in terms of patronage. However, the metropolitan area still suffers severe traffic congestion. This chapter will focus on the importance of improving bus services in the Chicago Loop area.

2.1 The Chicago Metropolitan Area

The Chicago Metropolitan Area is located in northeastern Illinois, consisting of six Illinois counties of Cook, Lake, McHenry, Kane, DuPage and Will (see Figure 2-1).

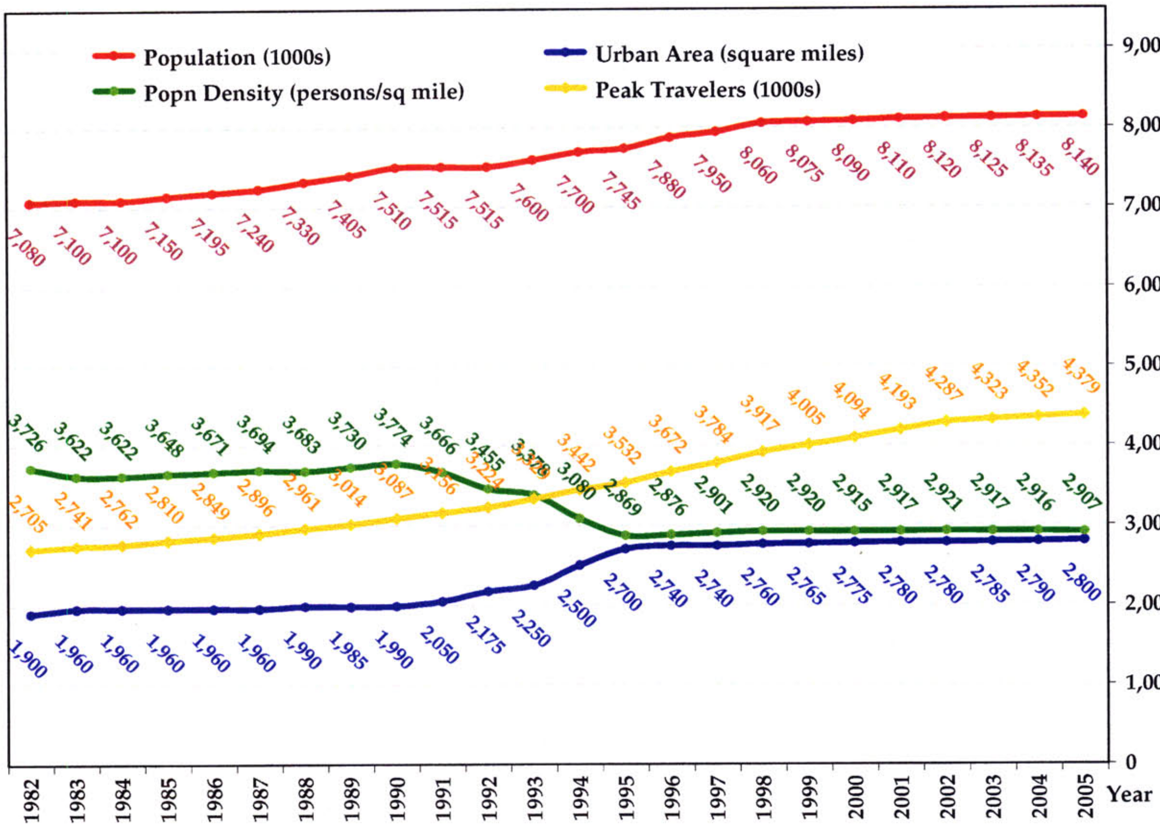
Figure 2-1 The Chicago Metropolitan Area



Source: adapted from http://www.metroplanning.org/about/mission.asp; retrieved March 20, 2009

In the last two decades, the Chicago Metropolitan Area has been growing considerably, both in terms of population and urban development. From 1982 to 2005, the population in the Chicago Metro Area increased from 7.08 million to 8.140 million, and its urbanized area expanded by 47.4% from 1,900 sq miles to 2,800 sq miles. Meanwhile the number of peak-hour travelers raised by 61.9%, from 2.705 million to 4.379 million (see Figure 2-2).

Figure 2-2 Changes of Population, Urban Area, and Travelers in Chicago, 1982-2005



Source: TTI, 2007

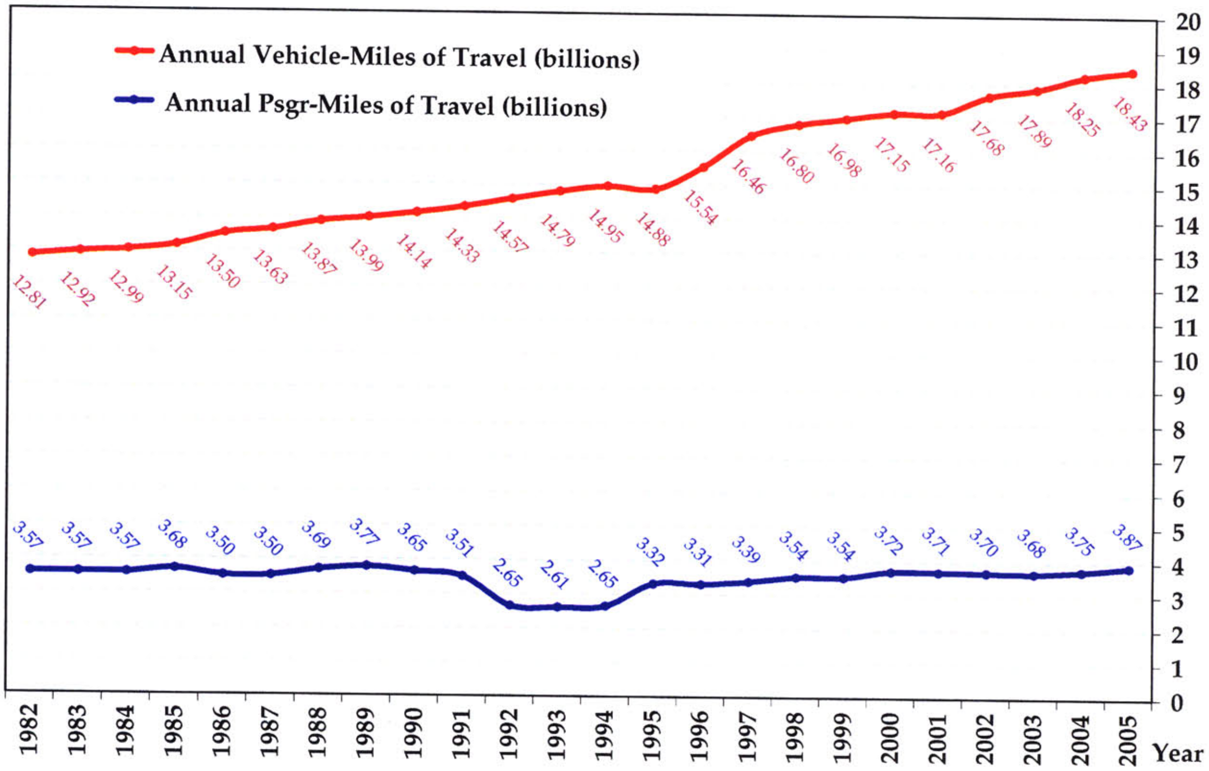
Despite of the escalation of population and peak-hour travelers, public transit share of commuting trips in the Chicago Metro Area decreased while car trips increased rapidly (see Table 2-1). As a result, the annual vehicle-miles of travel escalated drastically, from 12.81 billion in 1982 to 18.49 billion in 2005, yet the number of public transport passenger-miles of travel did not experience a significant change (see Figure 2-3).

Table 2-1 Changes of Travel Mode in Chicago, 2000 & 2006

Means of Transportation to Work	Year 2000		Year 2006	
	Workers	% Share of Total	Workers	% Share of Total
Transit (excluding Taxi)	497,319	13.26%	477,510	12.18%
Light Vehicle				
Drove Alone	2,590,171	69.06%	2,759,982	70.43%
Carpool	388,487	10.36%	358,627	9.15%
Bicycled or Walked	136,870	3.65%	131,903	3.37%
Worked at Home	104,106	2.78%	146,910	3.75%
Other (including Taxi)	33,644	0.90%	43,922	1.12%
Total	3,750,597	100.00%	3,918,854	100.00%

Source: U.S. Census Bureau, American Community Survey, Years 2000, 2006

Figure 2-3 **Travel by Transit and Automobile in Chicago, 1982-2005**



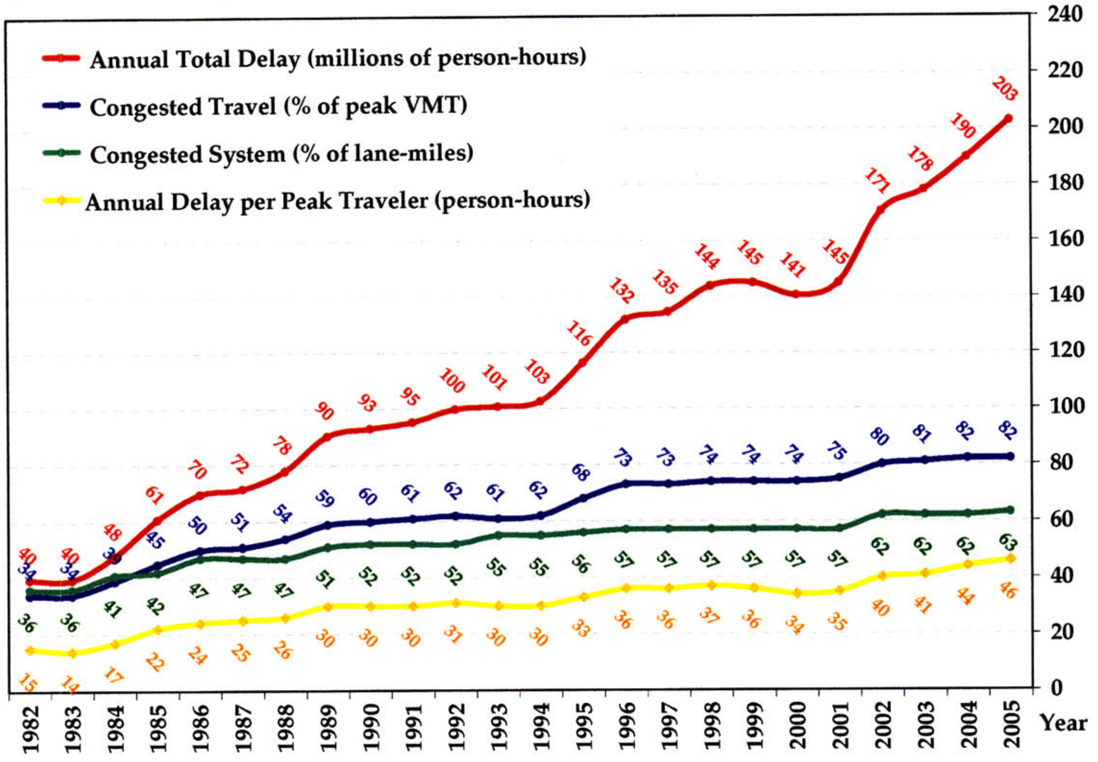
Source: TTI, 2007

2.1.1 *Traffic Congestion in Downtown Chicago*

As discussed in Chapter 1, Chicago has experienced a great increase in traffic congestion over the past two decades. From 1982 to 2005, annual hours of delay per traveler in the Chicago urban area increased from 15 hours to 46 hours, and the annual total delay escalated from around 40 millions of person-hours to 203 millions of person-hours (see Figure 2-4); gasoline wasted due to congestion increased from around 24 million to 142 million gallons. Both effects translate to a cost of 380 million and 3,970 million dollars, respectively (see Figure 2-5). In 2005, 82% of peak period travel in Chicago was congested, involving 63%of lane-miles, while the daily congestion reached 41% of all trips.

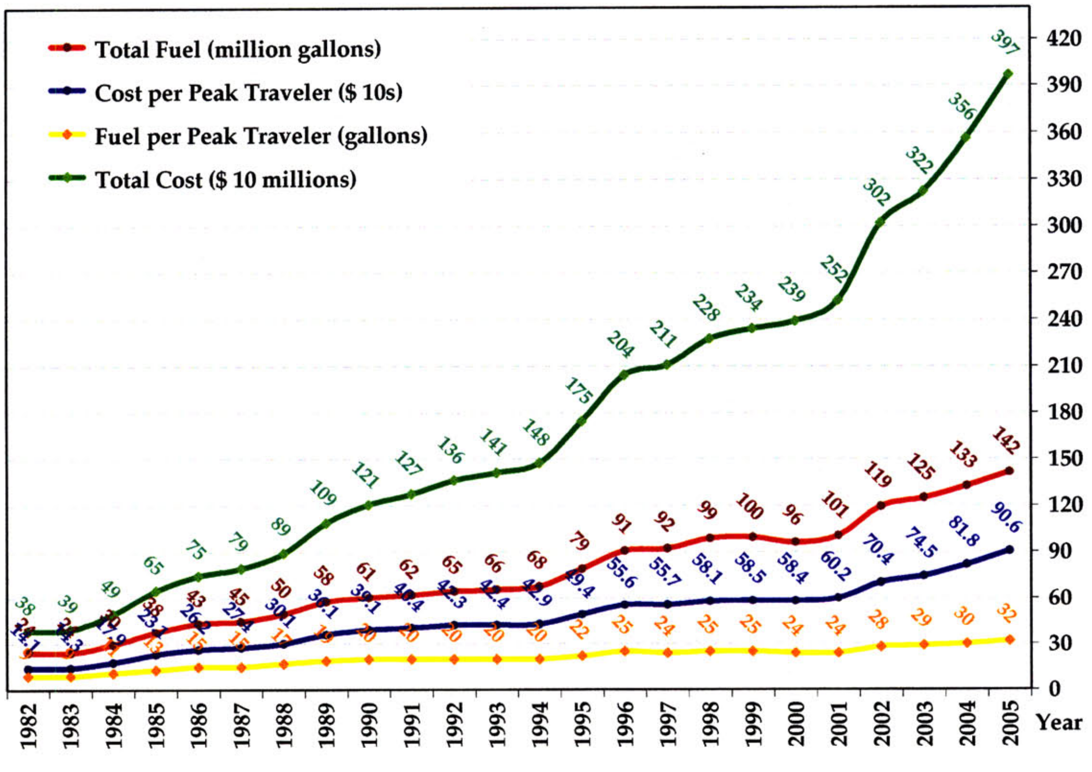
The level of congestion in Chicago ranked number three among 14 very large U.S. urban areas (see Figures 2-4 & 2-6, TTI, 2007). For an important trip, an average Chicago traveler should budget a travel time of 2.07 times of free-flow travel time to reach his/her destination, which ranked number one among 19 U.S. urban areas for 2007 (see Figure 2-7).

Figure 2-4 **Congestion Measures in Chicago, 1982--2005**



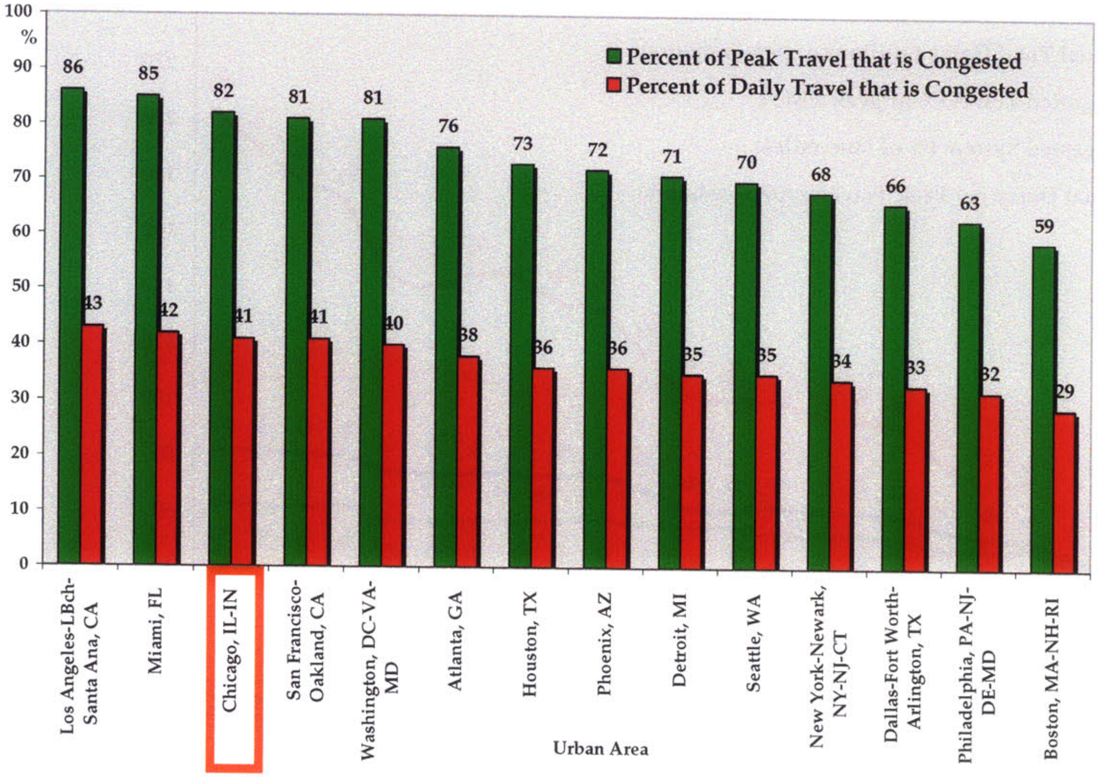
Source: TTI, 2007

Figure 2-5 **Fuel Waste and Costs due to Congestion in Chicago, 1982--2005**



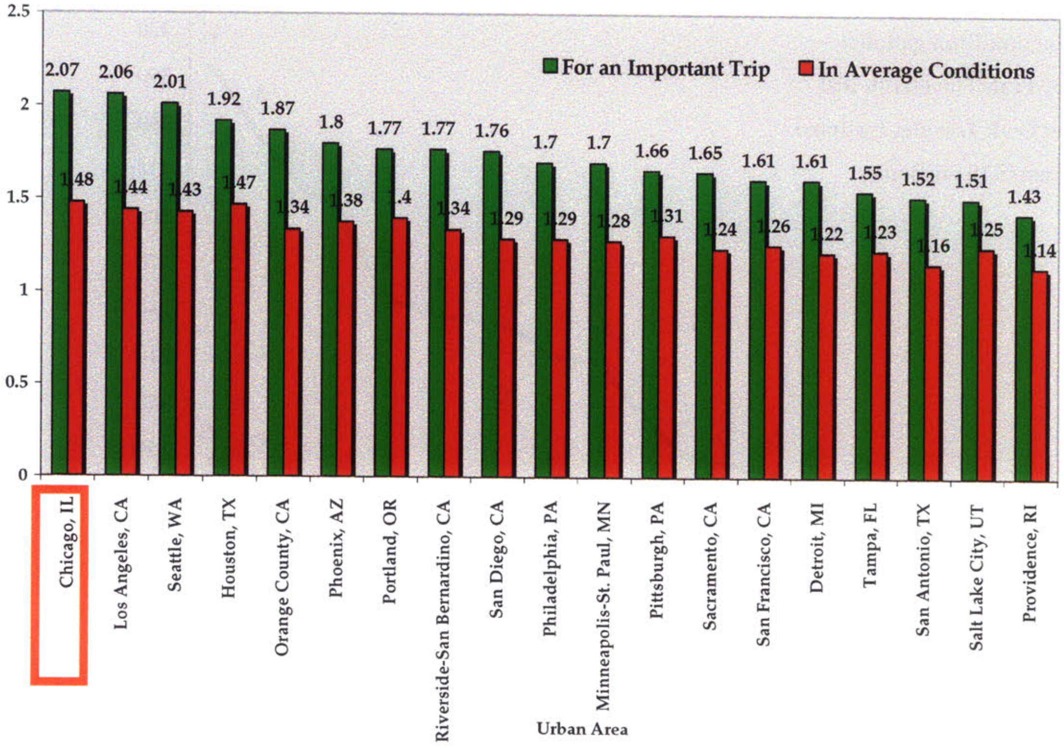
Source: TTI, 2007

Figure 2-6 Percentage of Congested Travel for Very Large U.S. Urban Areas, 2005



Source: TTI, 2007

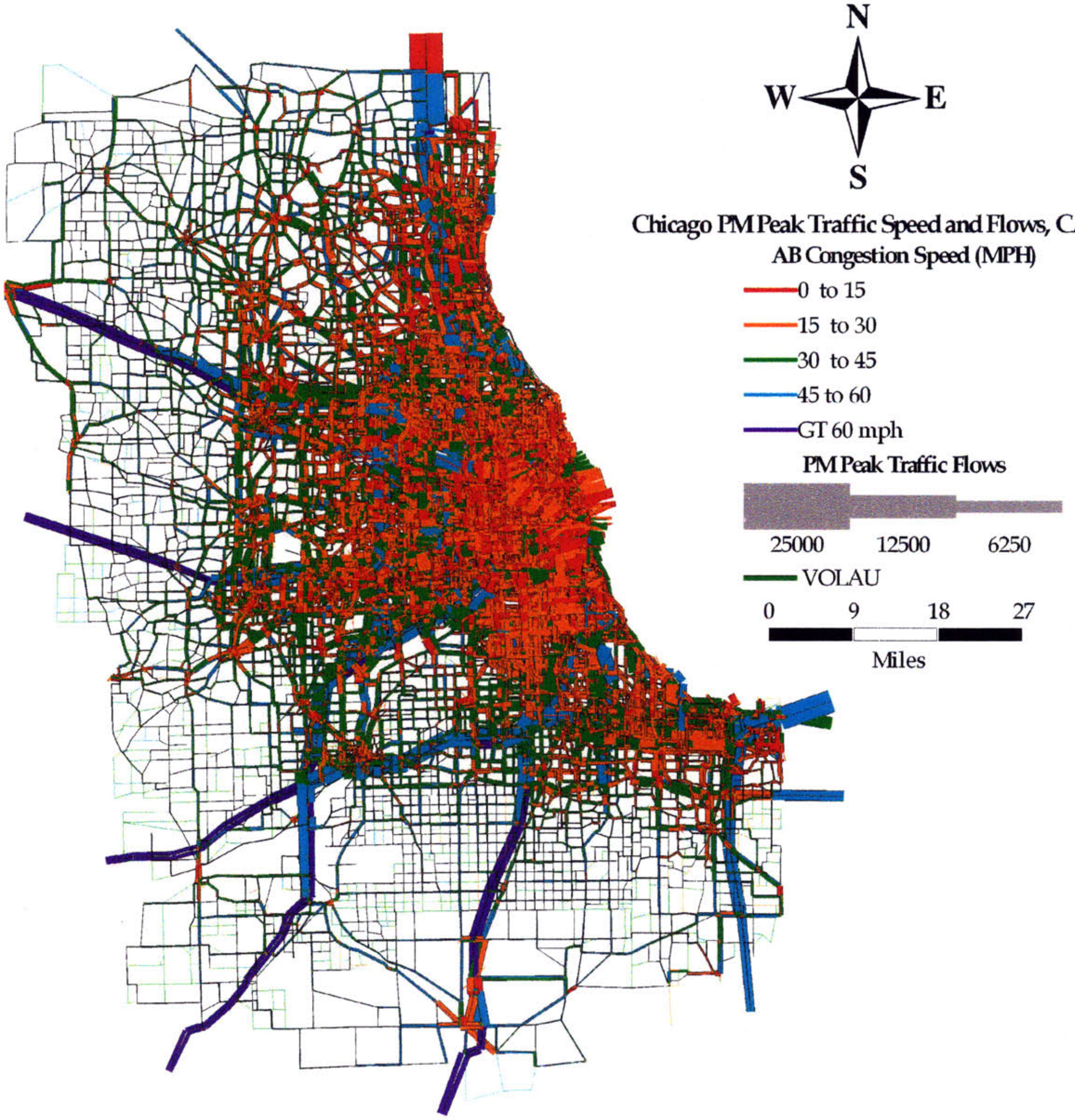
Figure 2-7 Travel Time Index for Planning a Trip to Arrive On-Schedule, 2007



Source: TTI, 2007

The Chicago Area Transportation Study (CATS, now reorganized as the Chicago Metropolitan Agency for Planning -- CMAP) estimated that in 2005, the average arterial speeds for the Chicago's central business district (CBD) was as slow as 12 mile per hour (mph), 17 mph for the non-central city, 24 mph for the suburban Cook County, and 25-37 mph for the five suburban and exurban collar counties (Figure 2-8).

Figure 2-8 PM Peak Traffic Speed and Flows in Cook County, CATS 2005



Source: the Chicago Area Transportation Study, 2005 and processed by Mikel Murga

2.2 Public Transportation in Chicago

In the Chicago Metro Area, the Regional Transportation Authority (RTA), the second largest public transportation system in North America as measured in terms of the number of unlinked passenger trips, oversees three major public transportation service providers—the Chicago Transit Authority (CTA), Metra commuter rail, and Pace suburban bus. In 2007, amongst the system wide unlinked 621.9 million passenger trips in the RTA system, 49.7% were served by the CTA bus system, 30.6% by the CTA rail system, 13.4% by the Metra commuter rail system, and 6.3% by the Pace bus system (see Table 2-2).

Table 2-2 **Historical Annual Ridership in the RTA System, 1980-2007**

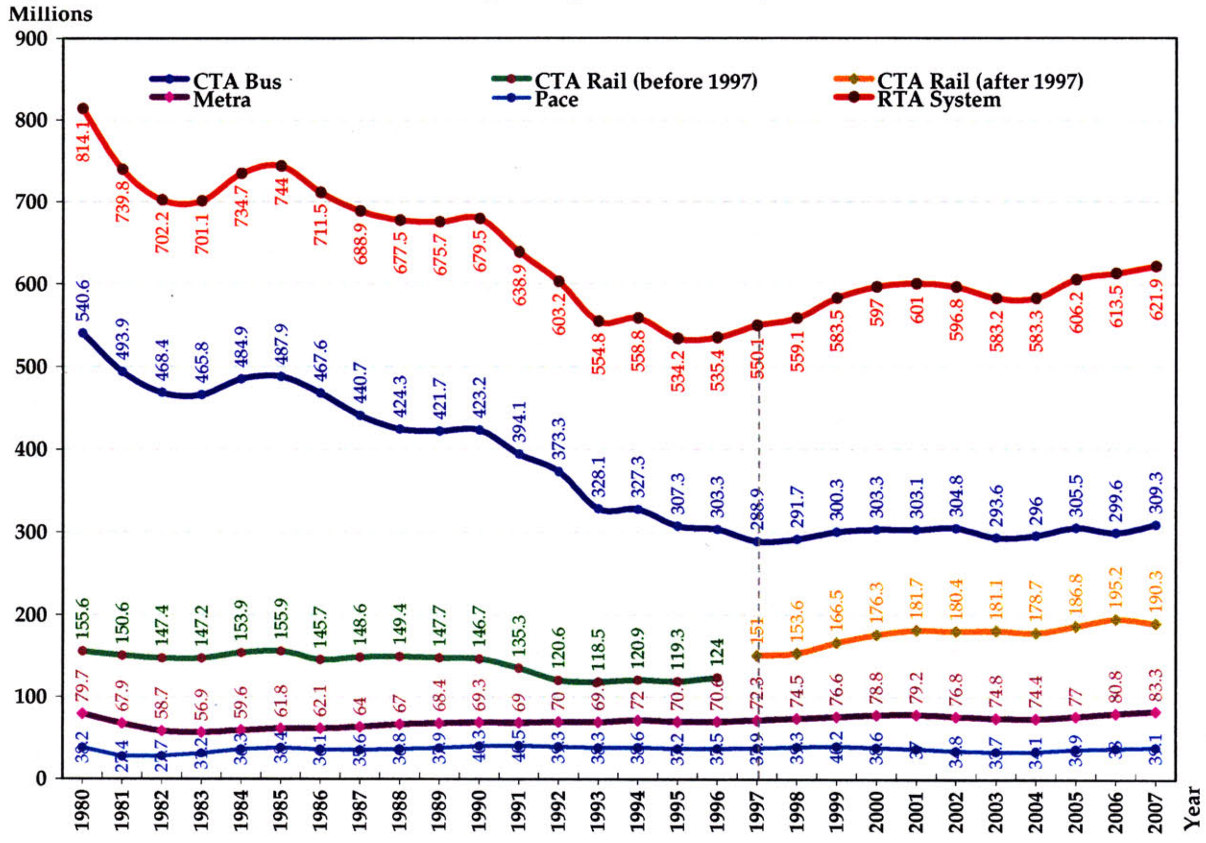
Year	RTA System Annual Unlinked Ridership	Ridership Share				
		CTA Bus	CTA Rail	Total CTA	Metra	Pace
1980	814.1	66.4%	19.1%	85.5%	9.8%	4.7%
1981	739.8	66.8%	20.4%	87.1%	9.2%	3.7%
1982	702.2	66.7%	21.0%	87.7%	8.4%	3.9%
1983	701.1	66.4%	21.0%	87.4%	8.1%	4.5%
1984	734.7	66.0%	20.9%	86.9%	8.1%	4.9%
1985	744.0	65.6%	21.0%	86.5%	8.3%	5.2%
1986	711.5	65.7%	20.5%	86.2%	8.7%	5.1%
1987	688.9	64.0%	21.6%	85.5%	9.3%	5.2%
1988	677.5	62.6%	22.1%	84.7%	9.9%	5.4%
1989	675.7	62.4%	21.9%	84.3%	10.1%	5.6%
1990	679.5	62.3%	21.6%	83.9%	10.2%	5.9%
1991	638.9	61.7%	21.2%	82.9%	10.8%	6.3%
1992	603.2	61.9%	20.0%	81.9%	11.6%	6.5%
1993	554.8	59.1%	21.4%	80.5%	12.6%	6.9%
1994	558.8	58.6%	21.6%	80.2%	12.9%	6.9%
1995	534.2	57.5%	22.3%	79.9%	13.2%	7.0%
1996	535.4	56.6%	23.2%	79.8%	13.2%	7.0%
1997	550.1	52.5%	27.4%	80.0%	13.1%	6.9%
1998	559.1	52.2%	27.5%	79.6%	13.3%	7.0%
1999	583.5	51.5%	28.5%	80.0%	13.1%	6.9%
2000	597.0	50.8%	29.5%	80.3%	13.2%	6.5%
2001	601.0	50.4%	30.2%	80.7%	13.2%	6.2%
2002	596.8	51.1%	30.2%	81.3%	12.9%	5.8%
2003	583.2	50.3%	31.1%	81.4%	12.8%	5.8%
2004	583.3	50.7%	30.6%	81.4%	12.8%	5.8%
2005	606.2	50.4%	30.8%	81.2%	12.7%	6.1%
2006	613.5	48.8%	31.8%	80.6%	13.2%	6.2%
2007	621.9	49.7%	30.6%	80.3%	13.4%	6.3%

Source: Regional Transportation Authority (RTA).

2.2.1 *Demand Served by the CTA Rail Network*

Figure 2-9 describes not only the historical annual trend of unlinked passenger trips in these three different public transport systems in the Chicago metropolitan area from 1980 to 2007, but also ridership changes in the region. While the general trend of the CTA bus ridership has been declining since 1980s, it has stabilized since 1997. On the other hand, CTA rail ridership has experienced significant growth during the last 10 years.

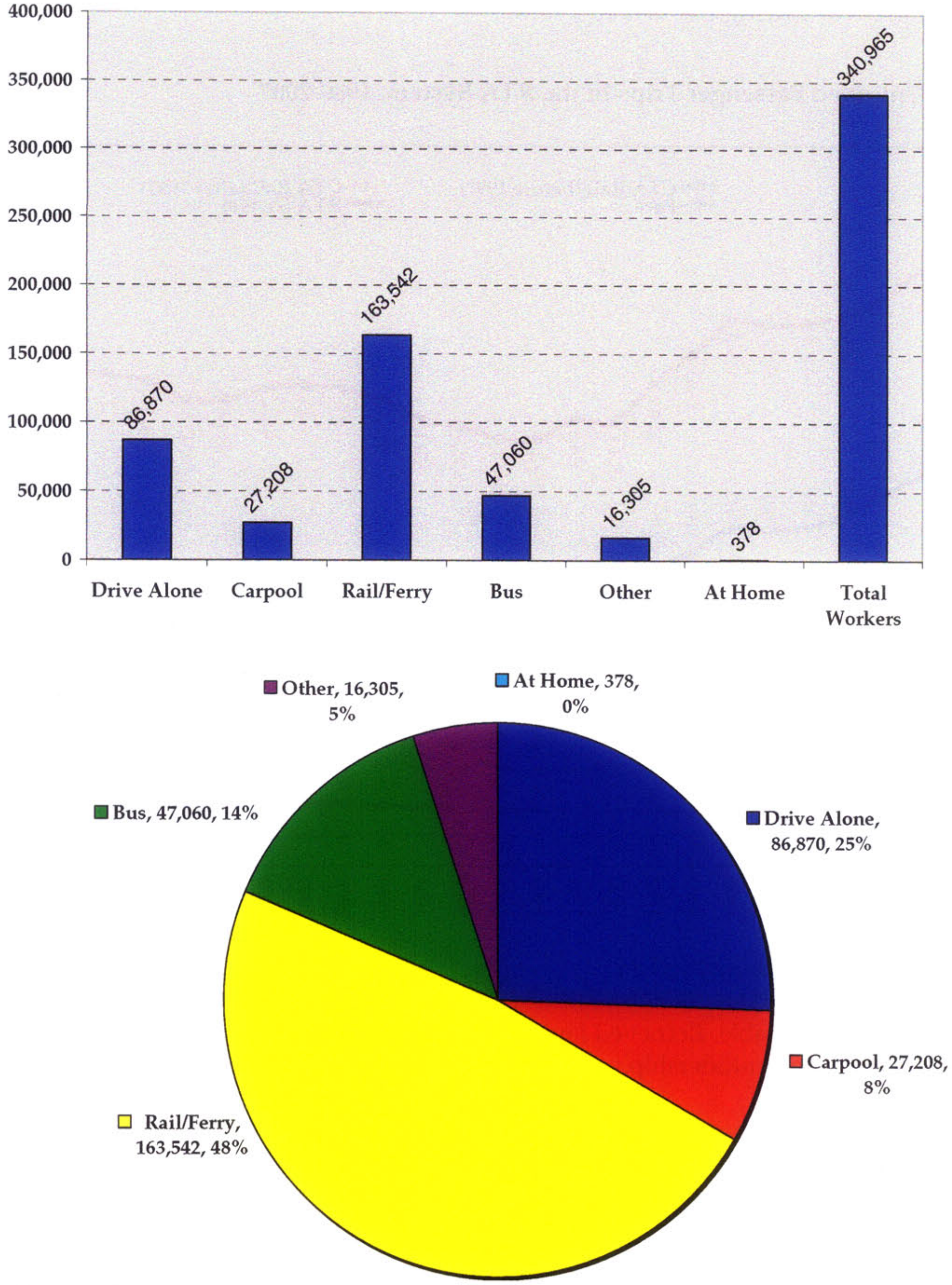
Figure 2-9 **Annual Unlinked Passenger Trips in the RTA System, 1980-2007**



Source: Regional Transportation Authority (RTA).
Note: starting in 1997, CTA rail ridership includes rail-to-rail transfers. CTA rail ridership figures before and after 1997 are not comparable. Retrieved January 20, 2009, from http://www.rtams.org/rtams/systemRidership.jsp

According to the Census Home-to-Work Journey 2000 survey data, among the 340,965 workers who worked in the downtown area, 47.9% of them commuted by rail, 13.8% by bus, and 25.4% drove alone (Figure 2-10). However the growth of the demand served by CTA Rail appears to have reached the capacity of the rail system during peak hours. This graph may well summarize the challenge of this thesis: How to improve the current bus level-of-service to achieve a significant transfer from the rail system, and more importantly, from the 87,000 commuters to the Loop Area who choose to drive.

Figure 2-10 Basic Work Trips and Mode Share Facts in the Loop Area

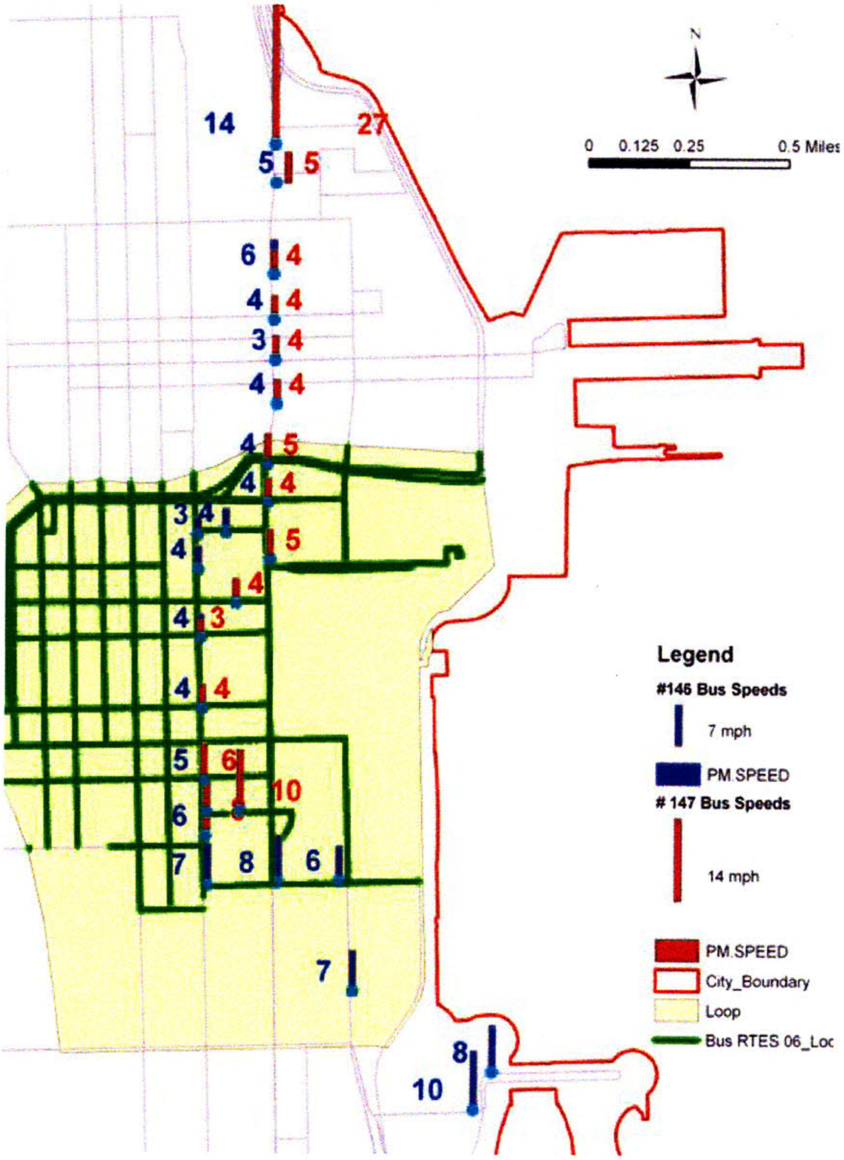


Source: CTPP 2000

2.2.2 *CTA Bus Level-Of-Service*

Due to traffic congestion, bus reliability and travel speed have decreased significantly. For example, the average speed of the CTA routes 146 and 147 during peak hour, in 2007, was 4 to 5 mph in downtown Chicago (Figure 2-11). Compared to the average travel speed of the general traffic in downtown Chicago, the difference of level-of-service between bus and auto has become more pronounced. As a consequence, mode share for car increased (see Table 2-1), and traffic congestion has augmented (Figures 2-3 & 2-4), generating a vicious cycle.

Figure 2-11 **Average Arterial Speeds in Cook County Area, 2005**



Source: AVL data obtained from the CTA, June, 2007; mapped by the author, 2008

The improvement of CTA transit level-of-service (LOS) in general, and of the bus system in particular, is a critical issue. This improvement should encourage more people to use public transit, reducing CO_2 emission and global warming, and decreasing air pollution and negative effects on public health. By improving its accessibility and lowering the need and cost of auto ownership, an effective transit system serves to attract new jobs to an area. In this context, it cannot be ignored that for Chicago to compete in the Global Economy, reliable and comfortable mass transit service will facilitate high job density, which in turn tends to induce more job agglomeration and higher synergies (Graham, 2007).

2.2.3 Congestion Relief Initiatives

In order to mitigate traffic congestion in Chicago downtown, the City of Chicago and CTA have committed to implement an integrated and aggressive program to reduce traffic congestion.

In April, 2008 the U.S. Department of Transportation announced the designation of Chicago, as a Congestion Reduction Demonstration ("CRD") Partner[1] under the terms of the CRD Agreement, *the City of Chicago and CTA* have committed to implementing an integrated and aggressive program to reduce traffic congestion with substantial Federal funding to support four sets of projects, including 1) Bus Rapid Transit (BRT), 2) loading zone fees, 3) variable parking pricing, and 4) a new private parking concession agreement. CTA is committed to dedicated BRT service along four corridors, serving as the first phase of a proposed city-wide arterial BRT network, including 1) 79th St. (State St.->Ashland Ave.); 2) Chicago Ave. (California Ave.-> Fairbanks Ct.); 3) Halsted St. (Lake St.-> North Ave.); and 4) Jeffrey Blvd. (87th St.->67th St.). (See Figure 2-12 for a more detailed BRT plan).

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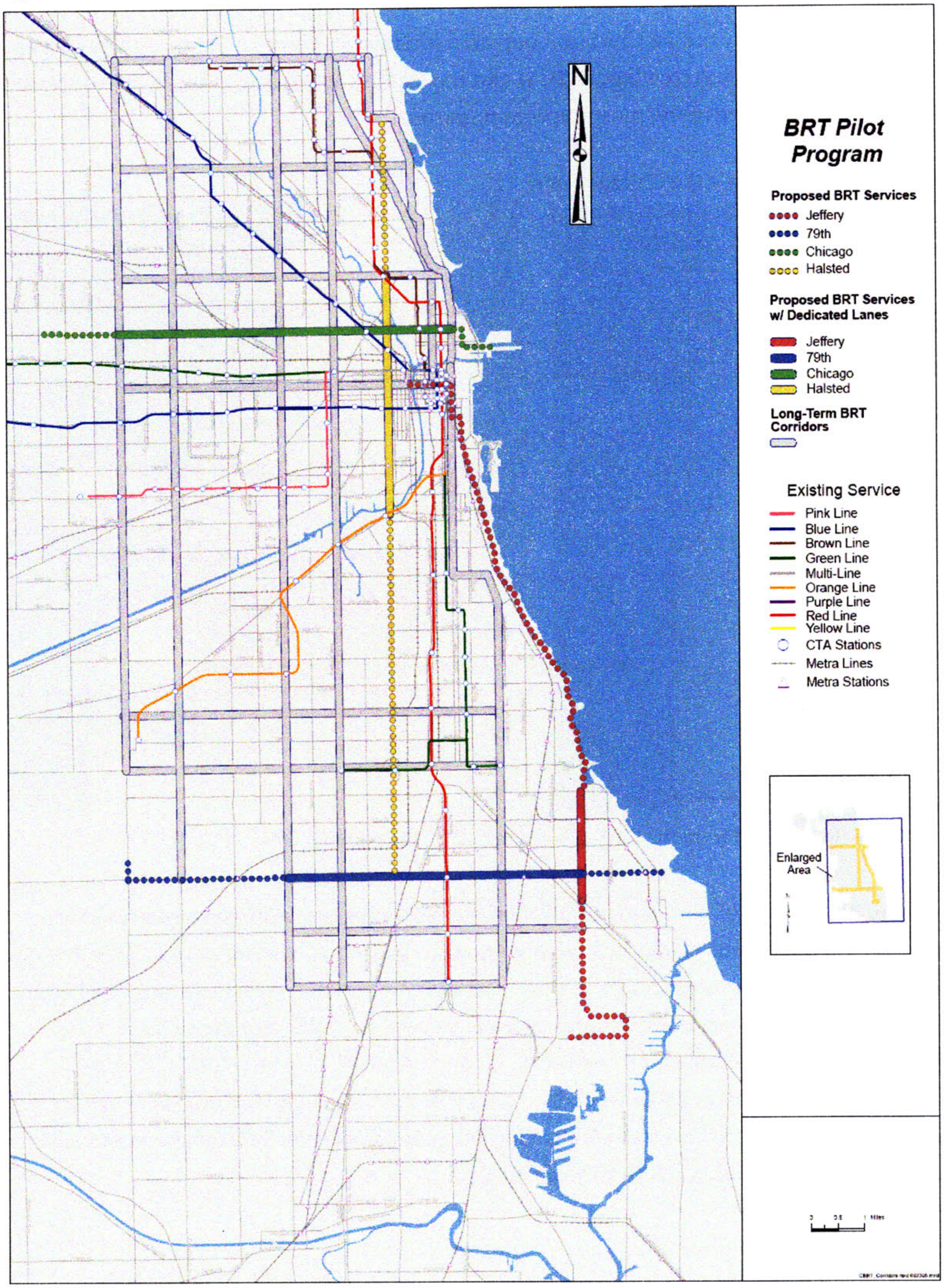
[1] Retrieved January 20, 2009, from http://www.crd.dot.gov/agreements/chicago.htm

Figure 2-12 BRT Corridors in the CTA BRT Pilot Program, 2008

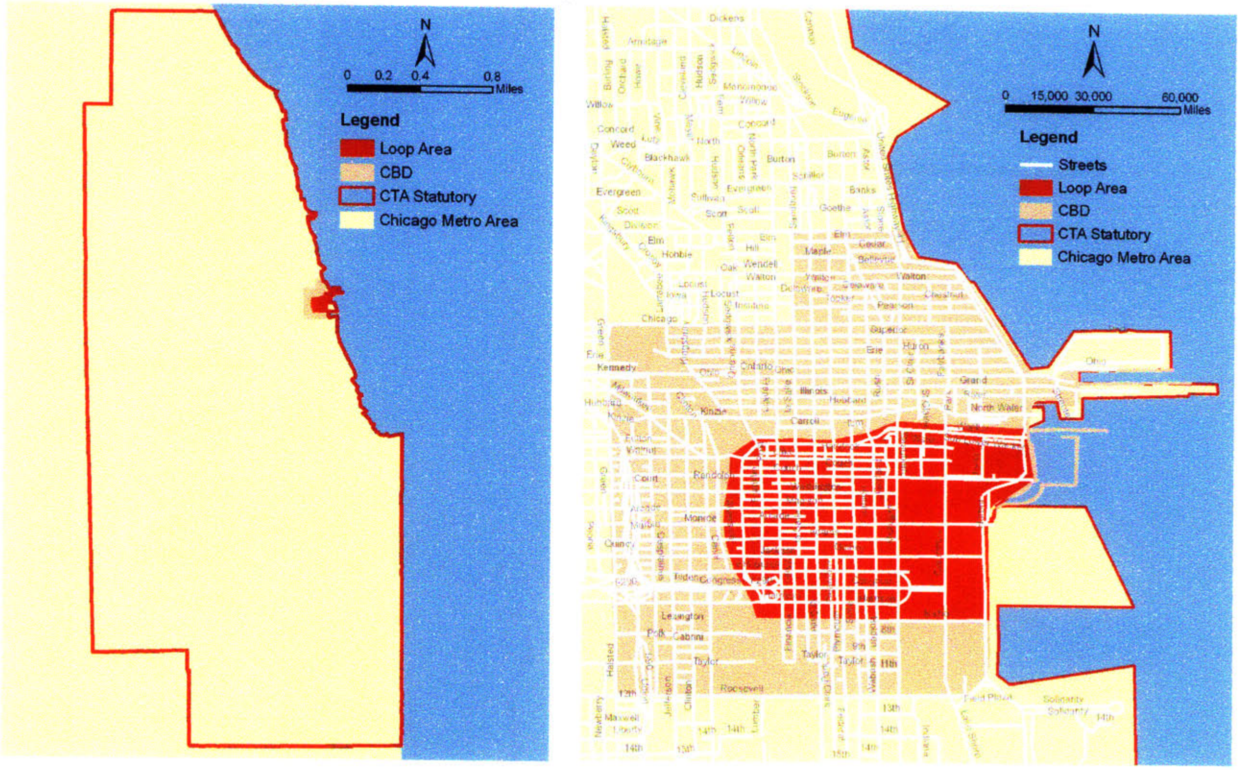


Source: the CTA, 2008

2.3 Targeting the Loop

This study focuses mainly on the Chicago Loop area (defined in Figure 2-13) for several reasons. The severe traffic congestion (see Figure 2-14) and its negative influence on bus level-of-service in the Chicago Loop is one of the most important reasons.

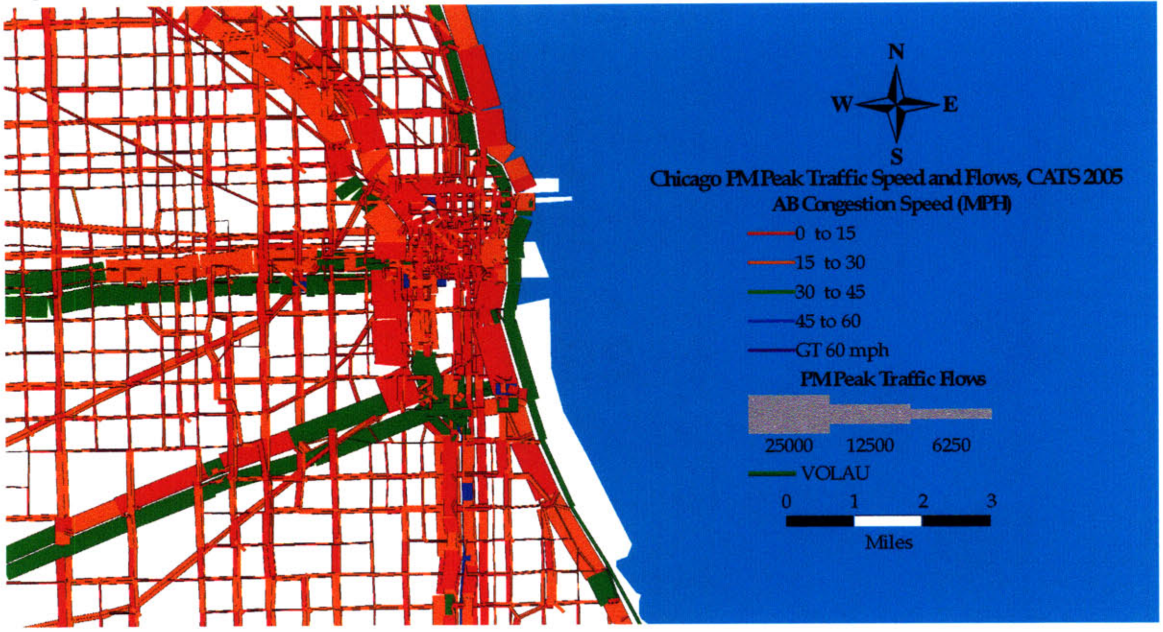
Figure 2-13 Study Area— the Chicago Loop



Source: GIS data obtained from the CTA, 2007; mapped by the author, 2009

Furthermore, the supply of and demand for the CTA bus service heavily concentrates in this area. 48 out of 155 CTA bus routes lie in the Loop area. Bus stops with more than 7500 average daily passenger boardings concentrate in three corridors within this area, including Michigan Ave, Washington Street, and Madison Street (see Figure 2-14). Although the Chicago Loop includes only 0.16% of the total CTA Statutory, it concentrates 3.4% of the total CTA bus passenger boardings on an average weekday (see Table 2-3). Thus improving bus Level-of-Service (LOS) in the Loop is crucial to improving the capacity of the CTA transit system and enhancing passenger mobility in the City of Chicago.

Figure 2-14 A Closer Look at the Traffic Congestion in Downtown Chicago, 2005



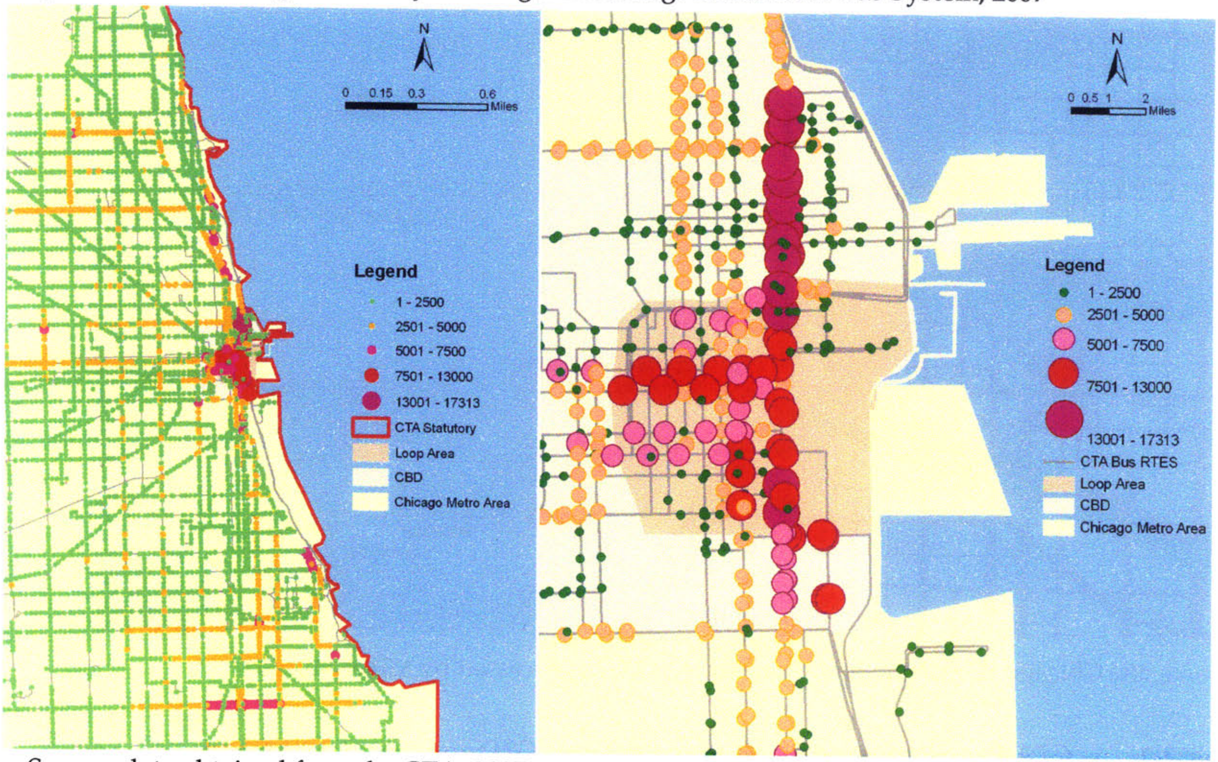
Source: the Chicago Area Transportation Study, 2005 as processed by Mikel Murga

Table 2-3 CTA Bus Supply and Demand in the Loop, CBD and the CTA Statutory

	Loop	CBD	CTA Statutory
Area (Square Mile)	1.15	3.75	738.69
Percentage	0.16%	0.51%	100.00%
Total Daily Bus Boardings	521,302	1,441,954	15,282,348
Percentage	3.41%	9.44%	100.00%
Bus Routes	48	57	156
Percentage	30.77%	36.54%	100.00%

Source: calculated by the author from the CTA GIS data, 2007

Figure 2-15 Average Weekday Passenger Boardings in the CTA Bus System, 2007



Source: data obtained from the CTA, 2007; mapped by the author, 2009

2.4 Peak Hour Period

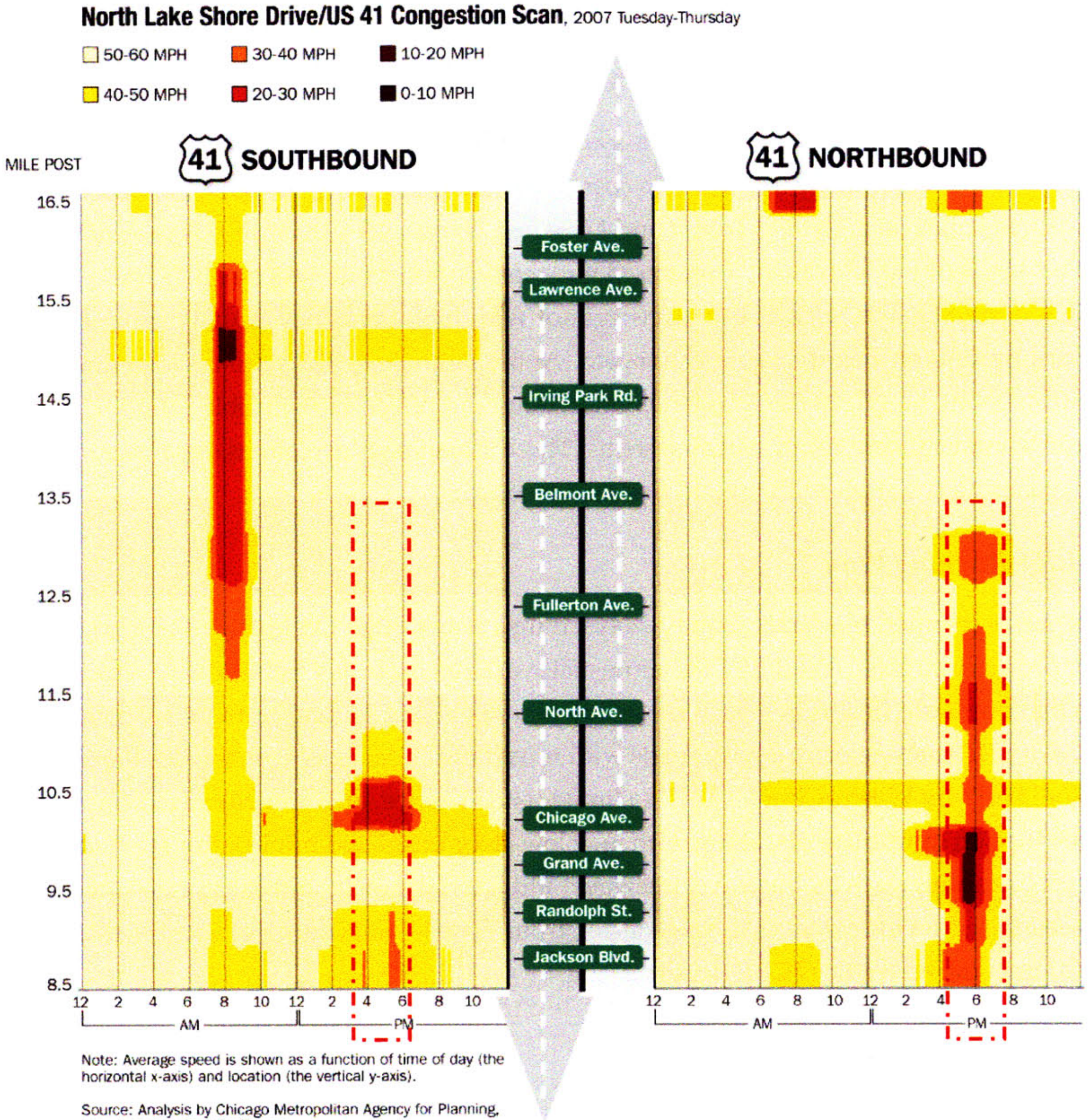
This research focuses on PM peak hours. There are several reasons for this. First, evidences confirm that traffic congestion in peak hour is more severe than off-peak hours, due mostly to commuting flows.

Second, our study area is confined to the Chicago Loop, the central business district of Chicago, which not only has a high agglomeration of jobs, but also serves shopping and recreational destinations. Commuting trips as well as shopping and entertainment trips concentrate more during PM peak hours than other time period of a day. The net result is that congested travel speed during PM peak hours is slower than other time periods.

Figure 2-16 provides evidence for the previous statement. The Chicago Metropolitan Agency for Planning (CMAP) developed mile-by-mile scans of traffic patterns to reflect the traffic congestion trends on the metropolitan expressways and the existing toll roads. Figure 2-16 shows North Lake Shore Drive/US 41 traffic condition. On Lake Shore Drive, between Jackson Blvd and Randolph Street, traffic congestion in Peak direction is more severe in PM peak hours than in AM peak hours.

The hypothesis is that PM Peak transportation conditions in the Chicago Loop represent the typical busiest time period of a day, and therefore if we can improve bus services during the busiest hours for the Chicago Loop, we will be able to solve problems in the rest of a day. To this end, the PM peak traffic data for the Chicago Loop was collected for this study in two distinct years as described later on.

Figure 2-16 PM vs. AM Peak Traffic Congestion Scan for North Lake Shore Drive


North Lake Shore Drive/US 41 Congestion Scan, 2007 Tuesday-Thursday

Note: Average speed is shown as a function of time of day (the horizontal x-axis) and location (the vertical y-axis).

Source: Analysis by Chicago Metropolitan Agency for Planning, based on data from Traffic.com.

Source: retrieved February 15, 2009 from http://www.cmap.illinois.gov/cmp/measurement.aspx # LSD_Foster_to_Jackson

Chapter 3 Bus Rapid Transit

The goal of this thesis is to study bus transit improvements using as the case study Chicago's impacts of Bus Rapid Transit (BRT). As one of the Congestion Reduction Demonstration (CRD) programs, it is necessary to discuss the definition and characteristics of BRT, survey the existing BRT systems in the world, and analyze the key elements that determine a successful BRT system.

3.1 Definition and Characteristics of BRT

Bus Rapid Transit (BRT) is a high speed bus system which usually operates in a dedicated right-of-way and has comparatively low start-up costs. BRT takes part of its name from *Rapid Transit* which includes high capacity *Rail Transit* and *Light Rail Transit*. However, BRT is very different from other kinds of Rapid Transit. Compared with conventional bus systems, BRT has prominent characteristics, such as exclusive right-of-way, high frequency, signal preemption, level boarding, and off-board fare collection, etc. At the same time, BRT requires lower initial capital investment, needs shorter implementation time, and offers more flexible routes compared to conventional rapid transit systems. These advantages explain its expansion in many developing countries with limited financial resources.

3.1.1 BRT Running Way

BRT can run on painted bus lanes, express ways, transit ways, High Occupancy Vehicle (HOV) lanes, or ordinary streets. A full BRT system usually uses an exclusive right-of-way which ensures that buses are free from delays caused by other vehicles. However, there are some examples of BRT running on ordinary roads with mixed traffic, such as Los Angeles Rapid Bus version of "BRT" on Wilshire Boulevards[1] (a limited-stop service, operating in mixed traffic with pre-emption traffic signals, along with new low-floor buses and mini-stations). Table 3-1 groups BRT running ways by busways, freeways, and arterial streets, and categorizes them into five classes, based on the extent of access control, from Type I—full control of access—to Type V, operation in mixed traffic (TCRP Report 90-2).

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[1] For more detail, please see "*Wilshire Bus Rapid Transit Project*" (retrieved February 20, 2009, from http://www.metro.net/projects_studies/wilshire/default.htm).

Table 3-1 **Running Ways Examples and Classification by Access Control**

Facility Type	Access Control	Class	Examples
Busways			
Bus Tunnel	Uninterrupted Flow—Full Control of Access	I	Boston, Seattle
Grade-Separated Runway			Ottawa, Pittsburgh
At-Grade Busway	Partial Control of Access	II	Miami, Hartford, Los Angeles(Orange Line)
Freeway Lanes			
Concurrent Flow Lanes	Uninterrupted Flow—Full Control of Access	I	Ottawa, Phoenix
Contra Flow Lanes			New Jersey Approach to Lincoln Tunnel
Bus-Only or Priority Ramps			Los Angeles
Arterial Streets			
Median Arterial Busway	Physically Separated Lanes Within Street Rights-of-Way	III	Curitiba(Brazil), Vancouver(Canada), Cleveland
Curb Bus Lanes	Exclusive/Semi-exclusive Lanes	IV	Rouen(France), Vancouver, Las Vegas
Dual Curb Lanes			New York City (Madison Avenue)
Interior Bus Lane			Boston
Median Bus Lane			Cleveland
Contra Flow Bus Lane			Los Angeles, Pittsburgh
Bus-Only Street			Portland(OR)
Mixed Traffic Flow	Mixed Traffic Operations	V	Los Angeles
Queue Jump/Bypass			Leeds(UK), Vancouver

Source: adapted and updated from TCRP Report, 90 (2), 2003

3.1.2 ITS in BRT

Intelligent Transportation Systems (ITS) have wide application in the transportation arena, and play an important role in ensuring that BRT services are reliable, fast, convenient and safe. Besides the automatic vehicle location (AVL), automatic passenger counting (APC), and automatic fare collection (AFC) systems that have been employed by the public transport sector (Zhao, Rahbee and Wilson, 2007), important ITS elements used by BRT systems include traffic signal preemption, and vehicle guidance and control.

Signal Preemption

There are two categories of signal priorities. One is conditional signal priority, known as "smart", which provides buses with green lights extensions only when buses are running late;

the other is passive signal priority, known as "dumb", which always provides signal priority when buses arrive.

3.1.3 BRT Stations, Vehicles, and Systems

BRT has larger capacity, better user amenities such as real time information, and modern stops; therefore it provides a better user perception of quality of service, thus leading to attract more riders.

Level Boarding

Many BRT stations have low platforms to serve low–floor vehicles, allowing level boarding to speed up passenger boardings and alightings, and enhance passenger accessibility.

Off-Board Fare Collection

Fare collection in BRT is usually off-board rather than on-board. Off-board fare collection allows boardings/alightings through all bus doors, thus saving passenger service time, lowering dwell time and therefore total travel time.

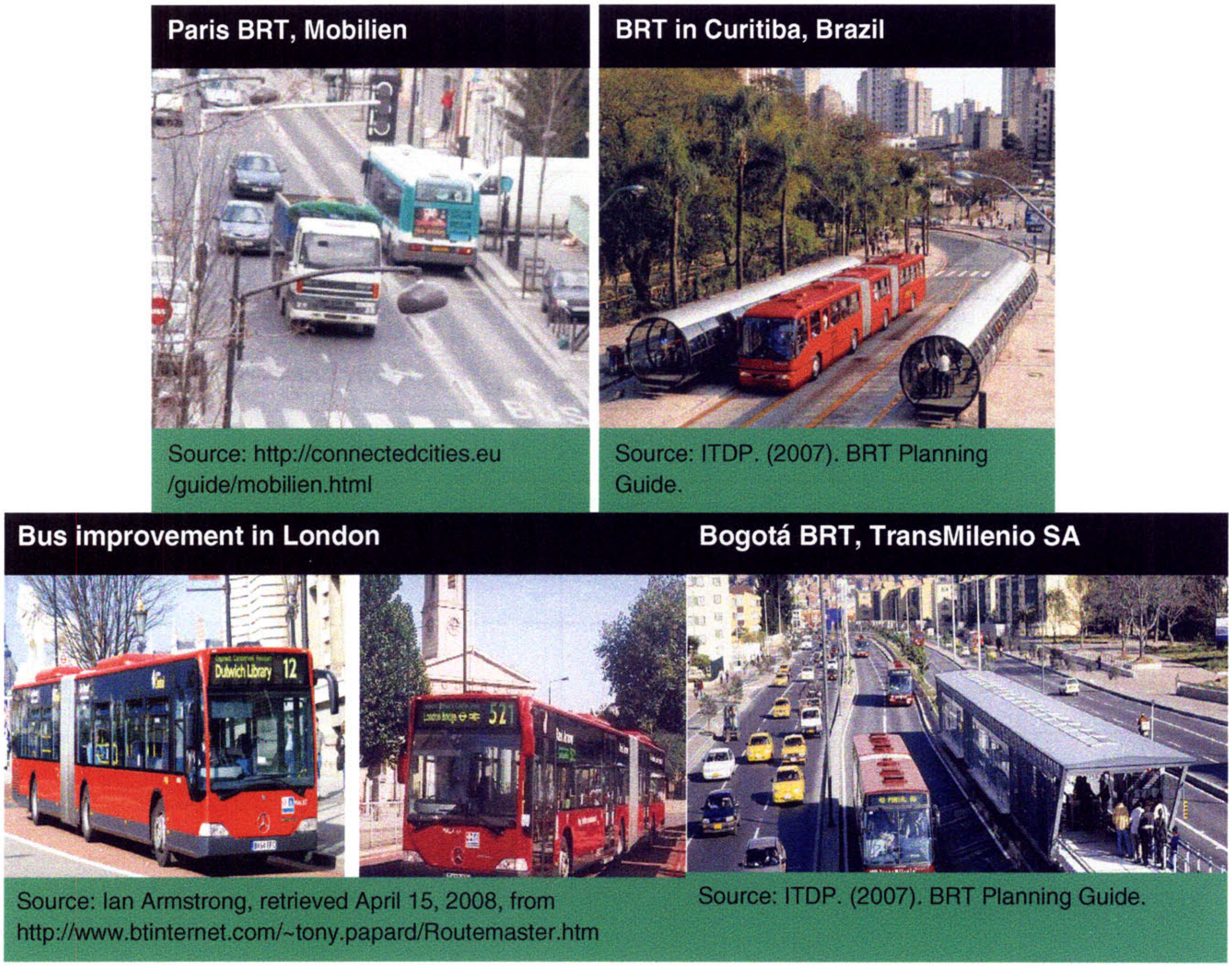
Brand Image

The branded image of BRT vehicles often highlights the systematic nature of BRT services. In order to distinguish the services of BRT from traditional buses, transit agencies emphasize branding the images of their new BRT systems. Examples include VIVA in Toronto, Silver Line in Boston, and Metro Rapid bus in Los Angeles, etc. These efforts of branding BRT try to change people's attitude towards bus services in order to escape the conventional appreciation of buses as uncomfortable, low quality or unreliable.

3.2 BRT around the World

Many studies have investigated worldwide existing BRT systems, their planning and implementation (Wright& Hook, 2007; TCRP Report 90-1, 2003). With the significant urban population growth around the globe and the urgent demand for improving mobility, Bus Rapid Transit systems have been widely developed across Continents. It is an inevitable trend that more countries will employ their own versions of Bus Rapid Transit which fit their societies and economic development.

Figure 3-1 **Bus Improvements and BRT Examples around the World**



Paris BRT, Mobilien

Source: http://connectedcities.eu /guide/mobilien.html

BRT in Curitiba, Brazil

Source: ITDP. (2007). BRT Planning Guide.

Bus improvement in London

Source: Ian Armstrong, retrieved April 15, 2008, from http://www.btinternet.com/~tony.papard/Routemaster.htm

Bogotá BRT, TransMilenio SA

Source: ITDP. (2007). BRT Planning Guide.

3.2.1 BRT in Latin America

Latin America is the pioneer in developing BRT systems. The opening of Curitiba's BRT system in 1974 represented the first step of BRT development (ITDP, 2007). Today, more than ten cities in Latin America have employed BRT, and many more are in planning or under construction. Cities that have established well-known BRT systems in Latin America include Curitiba, Sao Paulo (Brazil), Bogota (Colombia), and Mexico City (Mexico), etc.

3.2.2 BRT in North America

Even though BRT has been popular in developing countries where financial capacity is limited, many cities in North America have developed BRT because of its cost effectiveness in relieving traffic congestion and improving mobility in both short and long term, many cities in North America have developed BRT as well. These cities include Boston, Cleveland, Denver, Kansas

City, Los Angeles, Las Vegas, Miami, Minneapolis-St. Paul, Seattle, Toronto, and Vancouver. Table 3-2 lists characteristics of the ten North America BRT systems share.

Table 3-2 Characteristics of BRT Systems in North America

	Boston	Charlotte	Cleveland	Washington, D.C., Dulles	Eugene	Hartford	Honolulu	Miami	San Juan	San Jose
Bus ways		■			■	■		■		
Bus lanes	■	■	■			■		■		
Bus on HOV-Expressways		■		■			■		■	
Signal priority		■	■	■	■		■			
Fare collection improvements			■	■	■					■
Limited stops	■		■	■	■		■	■		■
Improved stations & shelters	■	■	■	■	■		■		■	
Intelligent transportation systems	■	■	■	■	■	■	■	■	■	■
Cleaner/quieter vehicles	■	■	■							

Source: TCRP Report, 90(2), 2003

3.2.3 *BRT in Europe*

In Europe, BRT or bus priority improvements have been developed in France, and in the United Kingdom. In Paris, the Mobilien network is designed to upgrade existing bus lines in Ile-de-France into BRT. Among the 150 lines planned for the Mobilien project, a dozen have been implemented and were operational in 2008[1]. Other French cities having BRT systems include Douai, Evry, and Nancy. In the UK, many cities, such as London, Runcorn, and Leeds, have guided bus systems, segregated busways and bus-only streets. Other European cities that have developed BRT are Amsterdam, Eindhoven, Utrecht in Netherlands, and Essen in Germany.

3.2.4 *BRT in Asia*

Prior to 2000, the BRT systems in Asia were limited in number and scope, however the spread of BRT in Asia has become more conspicuous since 2004 (Matsumoto, 2006). By September 2008, 21 cities in Asia have BRT systems in operation (Figure 3-2), and more are under construction or in the planning stage (Table 3-3).

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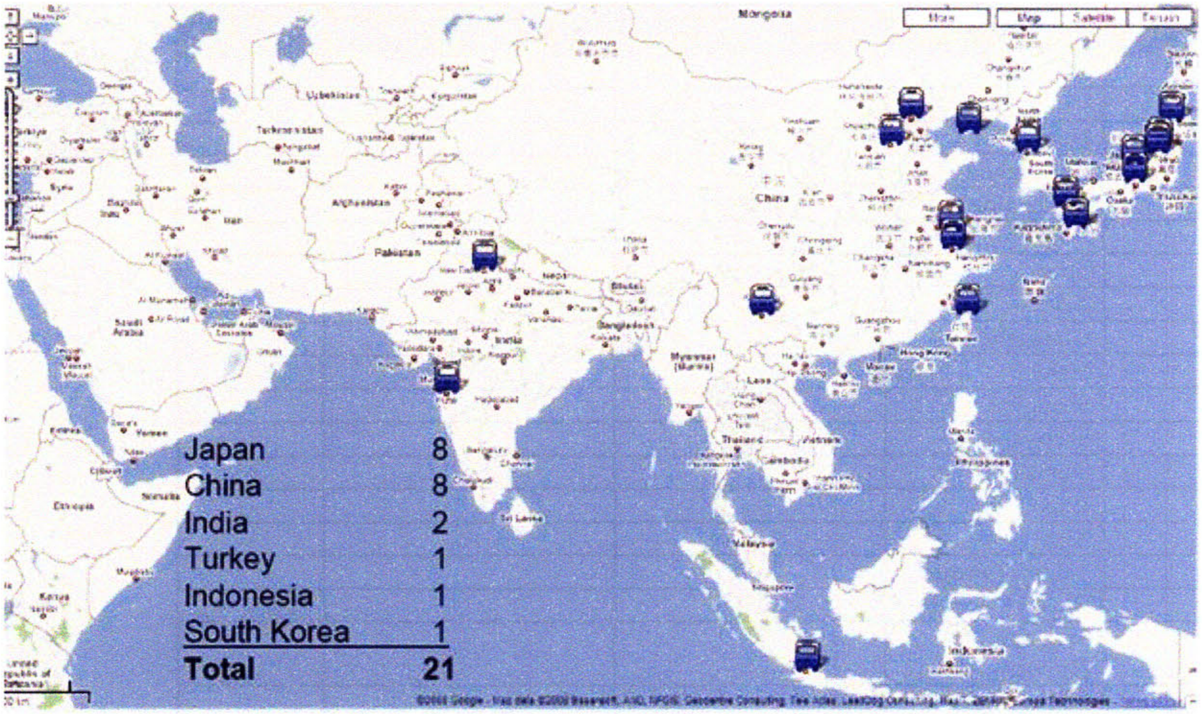
[1] Source: Retrieved March 20, 2009, from http://connectedcities.eu/showcases/mobilien.html,

Table 3-3 **A Selective List of BRT Systems in Asia**

Country	Cities	BRT Year Commenced	BRT Under Construction	BRT in Plan
China	Kunming	1999		
	Beijing	2004		
	Hangzhou	2006		
	Changzhou	2008		
	Chongqing	2008		
	Dalian	2008		
	Jinan	2008		
	Xiamen	2008		
	Guangzhou		2009	
	Hefei		2009	
	Shanghai			+
	Shenyang			+
	Shenzhen			+
	Wuxi			+
	Xi'an			+
	Taipei (Taiwan)	1996		
	Chiayi (Taiwan)	2007		
	Taoyuan (Taiwan)			+
	Taichung (Taiwan)			+
	Tainan (Taiwan)			+
India	Pune	2006		
	Mumbai		2009	
	New Delhi		+	
	Visakhapatnam		+	
	Chennai		+	
	Bangalore		+	
	Mangalore		+	
	Indore			+
	Ahmedabad			+
	Goa			+
	Vijayawad			+
Indonesia	Jakarta	2004		+
Israel	Haifa	2008		
Japan	Nagoya	2001		
Philippines	Cebu City			+
South Korea	Seoul	2004		+
Thailand	Bangkok			+
	Chiang Mai			+

Sources: retrieved February 16, 2009, from http://www.szplan.gov.cn/main/brt/, http://en.wikipedia.org/wiki/List_of_bus_rapid_transit_systems; http://61.60.38.100/en/sub-1.htm; http://www.cibus.com.tw/; http://urbantransportasia.blogspot.com/2006/02/success-story-seouls-2004-public.html; http://www.nctr.usf.edu/jpt/pdf/JPT%208-5%20Pucher.pdf; http://en.wikipedia.org/wiki/Yutreet_Line; http://www.thanakom.co.th/brt/home.html; http://www.citybusindore.com/pdf/executive_summary10.08.06.pdf; http://www.citybusindore.com/; http://english.chinabuses.com/news/0811/10004.html; http://en.wikipedia.org/wiki/TransJakarta. Note: + means ongoing as of January 2009.

Figure 3-2 Operational BRT Spatial Distribution in Asia by September 2008



Source: retrieved April 1, 09, from http://www.cleanairnet.org/caiasia/1412/articles-59592_operational.jpg

3.3 Benefit Measurements of BRT Systems

Overall, Bus Rapid Transit provides a higher quality of public transport service. It has larger capacity and higher speed compared to conventional buses, and has more flexibility compared to traditional rapid transit systems. As the technology of clean diesel has grown mature, BRT will help mitigate air pollution and save energy. Measurements that have been used to evaluate BRT system benefits include travel time, operation costs, fatality rates, fuel consumption, air pollution changes, and land development changes. Table 3-4 provides instances of benefits that different BRT systems have exemplified.

Table 3-4 Examples of BRT Benefits

SYSTEM	Benefit Aspects	Specific Benefits
Adelaide Guided Bus-way	Land Development	Tea Tree Gully area is becoming an urban village.
Bogotá TransMilenio	Travel Time Savings	32%
	Operational Costs	93% fewer fatalities. 40% drop in pollutants.
Brisbane South East Busway	Land Development	Up to 20% gain in property values near Busway. Property values in areas within 6 miles of station grew 2 to 3 times faster than those at greater distances.
Curitiba Median Busway	Operational Costs	30% less fuel consumption per capita.
Los Angeles Metro Rapid Bus	Travel Time Savings	23–28%

Ottawa Transit-way System	Operational Costs	150 fewer buses, with $58 million ($C) savings in vehicle costs and $28 million ($C) in operating costs.
	Land Development	$1 billion ($C) in new construction at Transit-way Stations.
Pittsburgh East Busway	Land Development	59 new developments within a 1500-ft radius of station. $302 million in land development benefits of which $275 million was new construction. 80% is clustered at station.
Porto Alegre	Travel Time Savings	29%
Seattle Bus Tunnel	Operational Costs	20% reductions in surface street bus volumes. 40% fewer accidents on tunnel bus routes.

Source: adapted from TCRP Report 90-2, 2003

3.4 What Makes a Successful BRT: from Plan to Implementation

Although bus rapid transit (BRT) may reduce negative effects of traffic congestion, it is critical to evaluate the impacts of such policies on different stakeholders (i.e., auto-drivers and bus-riders) before their implementation to assist policy-makers make sound decisions. Table 3-5 provides a comprehensive summary about the performance improvement goal that each BRT element aims to achieve.

Table 3-5 Linkages between BRT Characteristics and System Performance

	System Performance				
BRT Characteristics	Travel Time Saving	Reliability	Identity & Image	Safety & Security	Capacity
RUNNING WAY					
Running Way Segregation	■	■	■	■	■
Running Way Marking			■		
Running Way Guidance	■		■	■	
STATIONS					
Station Type	■		■	■	■
Platform Height	■	■	■	■	■
Platform Layout	■	■			■
Passing Capability	■	■			■
Station Access			■	■	
VEHICLES					
Vehicle Configurations	■	■	■	■	■
Aesthetic Enhancement			■	■	
Passenger Circulation Enhancement	■	■	■	■	■
Propulsion Systems	■		■		
FARE COLLECTION					
Fare Collection Process	■	■	■		■
Fare Transaction Media	■	■	■	■	■
Fare Structure	■		■		■

INTELLIGENT TRANSPORTATION SYSTEMS					
Vehicle Prioritization	■	■	■		■
Driver Assist and Automation Technology	■	■	■	■	■
Operations Management	■	■		■	■
Passenger Information	■	■	■	■	
Safety and Security technology				■	
Support Technologies					■
SERVICE AND OPERATING PLANS					
Route Length		■			
Route Structure	■		■		
Span of Service		■			
Frequency of Service	■	■		■	■
Station Spacing	■	■			

Source: Diaz, et al., 2004.

Chapter 4 A Microscopic Traffic Simulation Approach

The purpose of this study is to develop a microsimulation model as a planning and a decision-making tool 1) to explore the potential for bus service improvements, and 2) to examine the impacts of different BRT scenarios on automobile traffic. Proposed indicators to evaluate the alternatives include: 1) bus reliability, 2) travel time and travel speed for buses and automobiles, and 3) total passenger-hours delay for buses and automobiles.

4.1 Microscopic Traffic Simulation in Theory and Practice

The U.S. DOT Federal Highway Administration describes a microscopic traffic simulation (microsimulation) model as a traffic analysis tool, which "simulates the movement of individual vehicles based on car-following and lane-changing theories." In a traffic microsimulation model, "vehicles enter a transportation network using a statistical distribution of arrivals (a stochastic process) and are tracked through the network over small time intervals (e.g., 1 second or a fraction of a second). Upon entry, each vehicle is assigned a destination, a vehicle type, and a driver type."[1]

Table 4-1 A List of Popular Microscopic Traffic Simulation Packages

Model	Organization	Country
Aimsun	Transport Simulation Systems	Spain
CORSIM	Federal Highway Administration & University of Florida	USA
MITSIMLab	Massachusetts Institute of Technology	USA
Paramics	Quadstone Paramics Ltd within Portrait Software PLC	UK
TransModeler	Caliper Corporation	USA
VISSIM	PTV AG	Germany

Note: for a completed list, please refer to Algers, Bernauer, Boero, Breheret, Taranto, Dougherty, Fox, and Gabard (2009).

Table 4-1 provides a list of popular microscopic traffic simulation software packages worldwide. Among these microsimulation packages, MITSIMLab is the only one for research purposes, while the rest are commercial packages.

According to the traffic conditions that existing microsimulation models can apply to, Algers and Bernauer et al (2009) categorize a full list of microsimulation models into four classes: 1) urban, 2) motorway, 3) combined and 4) other models usually developed for very specific objectives.

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[1] Retrieved January 20, 2009 from http://ops.fhwa.dot.gov/trafficanalysistools/tat_vol1/sect4.htm

4.2 Advantages of a Microsimulation Approach

In order to explore BRT's full potential, a microsimulation approach has been employed in this thesis. Microsimulation is very powerful, because:

- It can describe all the factors of the traffic system, including double parking, random traffic effects, and the non-linear behavior of traffic congestion.
- It allows us the analysis of a network rather than a single corridor. This is important as it permits to reassign automobile traffic to provide priority for buses.
- It allows to explore different scenarios of BRT and run sensitivity analysis for each scenario.
- It can assist decision makers/transportation planners/traffic engineers to make well informed decisions.
- It facilitates "visioning" of alternatives in a non-technical manner.

4.3 Objectives of Using a Microsimulation for This Research

A microscopic, time-step and behavior based multi-purpose traffic simulation package developed by PTV VISSIM has been used for this study. By employing VISSIM microsimulation package and preparing the Chicago Loop microsimulation model, we aim to achieve the following objectives, as listed in Table 4-2.

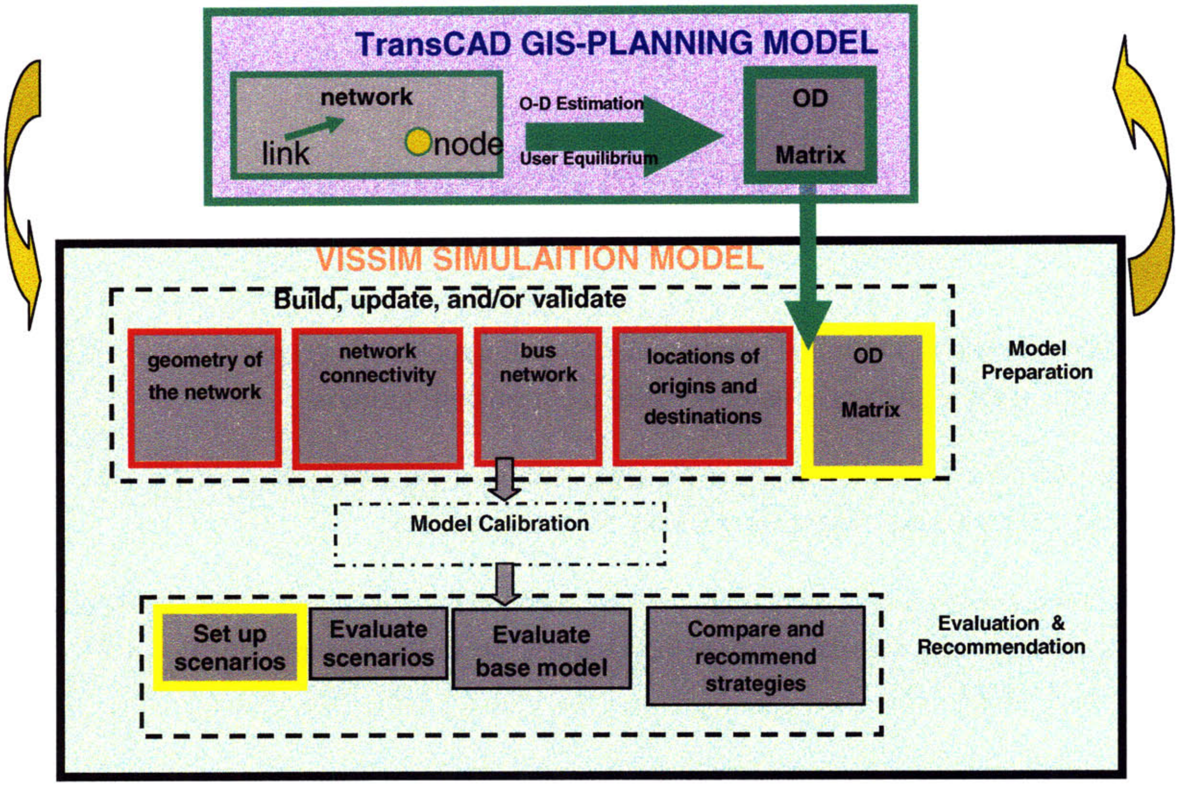
Table 4-2 Objectives and Measurements of Microsimulation for This Research

Objectives	Methods/Measurement
Evaluate the current base-case traffic conditions in the Chicago Loop	Automobile travel time and speed, and delay time
Evaluate the current base-case bus performance in the Chicago Loop	Bus reliability, travel time and speed, and delay time
Setting up scenarios of bus improvements in the Chicago Loop	Changing bus facilities(stop spacing/locations, dedicated bus-lanes, etc) in the VISSIM model
Evaluate bus performance in different scenarios in the Chicago Loop	Bus reliability, travel time and speed, and delay time
Evaluate traffic conditions in different scenarios in the Chicago Loop	Automobile travel time and speed, and delay time

4.4 Microsimulation Model Preparation for the Chicago Loop

Figure 4-1 shows the framework and process of the microsimulation model preparation while the preparation of this VISSIM model described later in the section.

Figure 4-1 **Microsimulation Model Preparation Framework**



A preliminary network for the VISSIM microsimulation model was imported from a model built in a signal optimization software package SYNCHRO[1].

However, in order to calibrate the model, the author had to implement several major enhancements by revising and updating the model. The model preparation process included 1) full revision the traffic network, 2) verification of all traffic signal controls, 3) exact determination of origins-destinations, and parking lots, 4) estimation of an auto OD matrix and 5) update of the bus network in terms of schedule, passenger loading, and dwell times.

The first two elements (traffic road and street characteristics, and traffic signals) were revised and validated based on the author's field trips to Chicago, together with ample reliance of Google Maps and Microsoft Live Maps. Parking lots were validated based on the data from the

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[1] The first version of the model was prepared by a previous MIT graduate student, Ajay Martin, who worked as an intern in the Mayor's Office at the City of Chicago in the summer of 2004.

City of Chicago. The OD matrix was estimated from traffic counts data obtained from the City of Chicago (2004) by using the transportation planning package, TransCAD, while the bus network was modeled based on the CTA bus historical data.

4.4.1 *Basic Graphic Theory*

To understand the representation of the traffic network in the microscopic traffic simulation model, it is helpful to start with some basic graphic theory that has been used to prepare traffic networks.

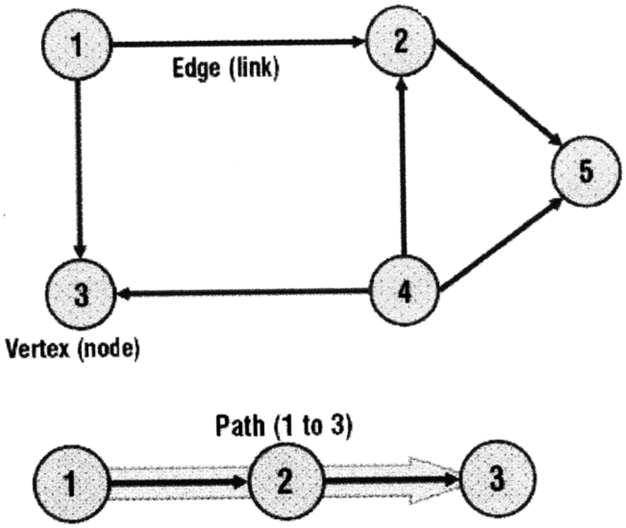
A graph is a symbolic representation of a network and of its connectivity. It implies an abstraction of a real world traffic network so as to simplify it as a set of linked nodes (Rodrigue, et al, 2006).

Vertex (Node): A node is a terminal point or an intersection point of a graph. It is the abstraction of a location such as a road intersection or transport terminal.

Edge (Link): An edge is a link between two nodes. A link, having a direction, abstracts a transport infrastructure supporting movements between nodes.

Path: A path is a sequence of links that are traveled in the same direction. Searching all possible paths in a graph is a fundamental attribute in measuring accessibility and traffic flows. (Rodrigue, et al, 2006)

Figure 4-2 Graph Representation of a Transportation Network and a Path



Source: adapted from Rodrigue, et al, 2006.

4.4.2 *Traffic Network Components*

As the network had been built previously by importing data from a model prepared in SYNCHRO, the author did substantive checks and updates to the network based on the latest aerial images obtained from Google Earth. The updates include correcting the topological locations of the links, verifying the connector locations and their topological relations with links, validating the relationships of links and nodes, and verifying the number of lanes of each link. In this section, the traffic network components of the Chicago Loop VISSIM model are explained to help readers better understand how the traffic network has been prepared in VISSIM. Definitions of the terms are adopted from the VISSIM 4.30 User Manual.

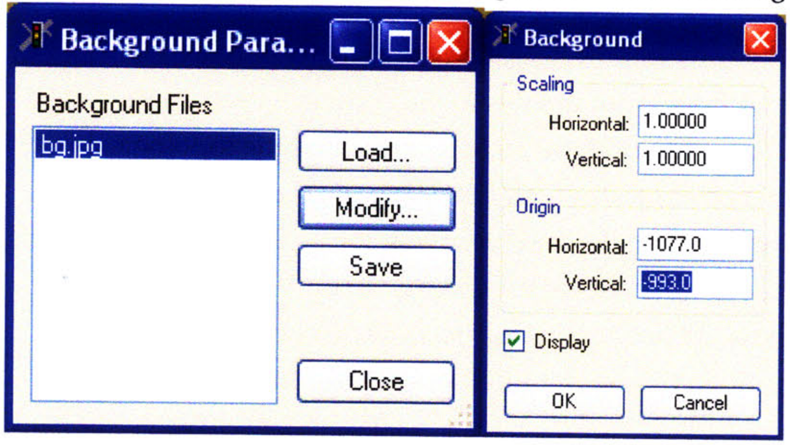
Scale

Before starting to code the VISSIM network, one needs to confirm the scale, so that the measurement of travel time and travel speed are not affected by that basic fact. This can be done by using a scaled background graphic. In this research, the background of Chicago Loop image was captured from Google Earth, and the scale was verified in VISSIM. Figure 4-3 is a snapshot of the Chicago Loop VISSIM Model that was developed. Figure 4-4 illustrates how to adjust the background graph and set the right scale for the VISSIM model.

Figure 4-3 Chicago Loop VISSIM Model Road Network with Background Image

Source: the author, 2008

Figure 4-4 Background Scale Setting in the VISSIM Chicago Loop Model



Background Files
bg.jpg

Scaling
Horizontal: 1.00000
Vertical: 1.00000

Origin
Horizontal: -1077.0
Vertical: -993.0

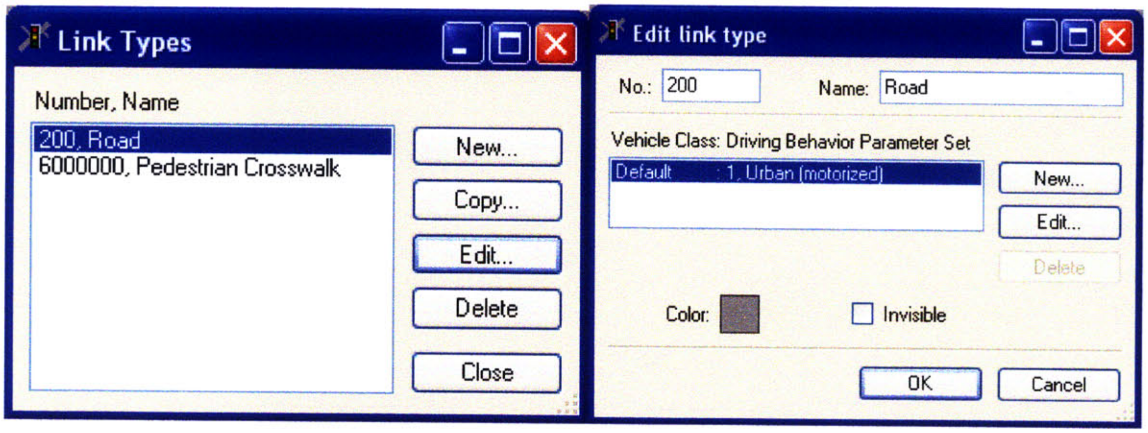
☑ Display

Source: the author, 2008

Links

For creating and updating the links, the road network was traced against the satellite image of the study area. Each road section on a satellite image was represented by one link in the microsimulation model. Several link types were defined (see Figure 4-5), which control the driving behavior or characteristics of the link; the length of it; the name of the link, i.e. a real street name; and the number of lanes on each link. Figure 4-6 provides an example of setting a link in VISSIM. The figure shows the same road section, as a center-line view, while the left-hand side one is a normal view. VISSIM also allows displaying 3D parameters such as height, and thickness of the link, which is useful for public presentations.

Figure 4-5 Link Types in the Chicago Loop VISSIM Model



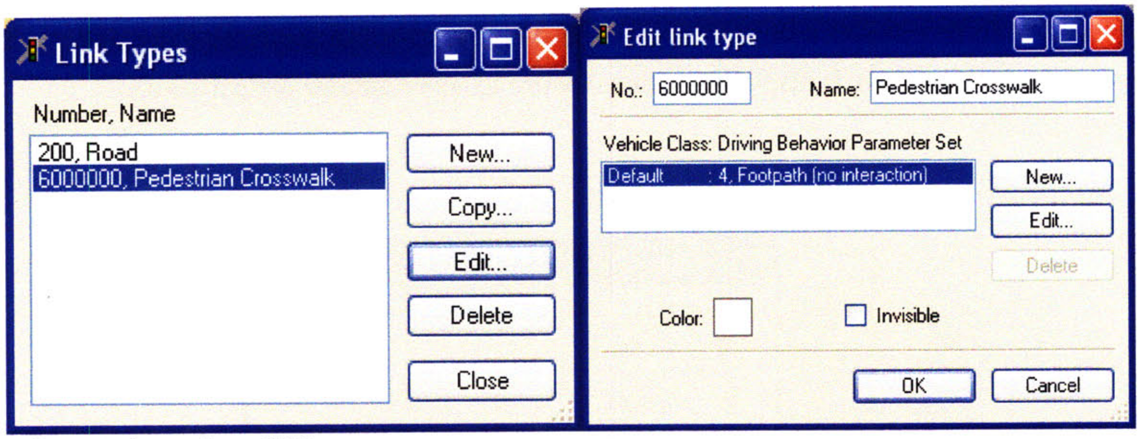
Number, Name
200, Road
6000000, Pedestrian Crosswalk

No.: 200 Name: Road

Vehicle Class: Driving Behavior Parameter Set
Default : 1, Urban (motorized)

Color:

☐ Invisible



Number, Name
200, Road
6000000, Pedestrian Crosswalk

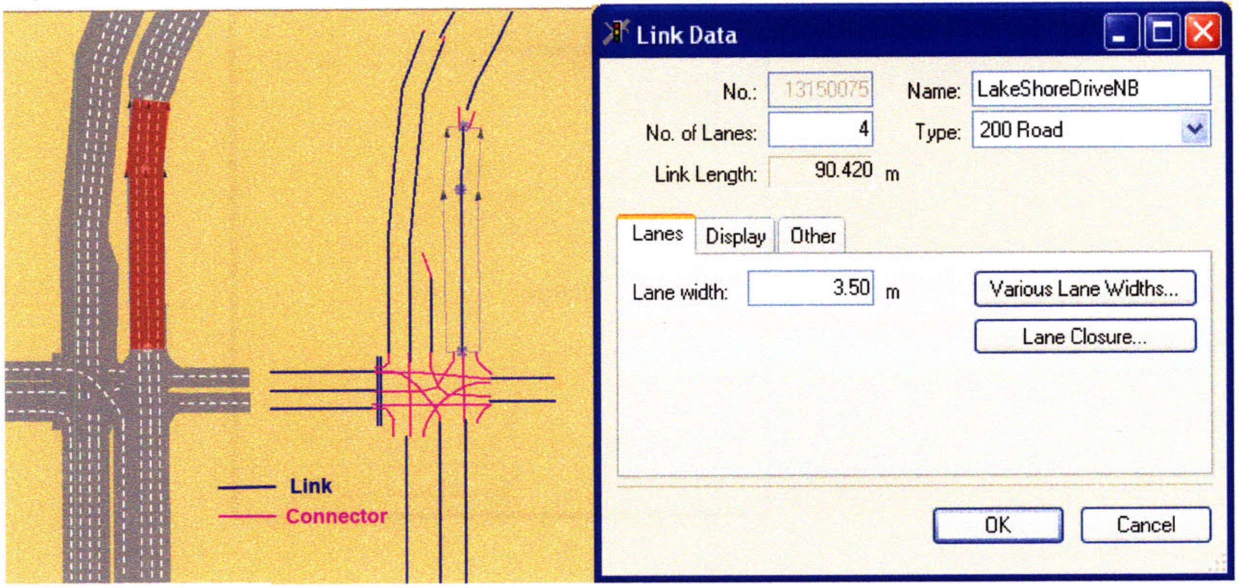
No.: 6000000 Name: Pedestrian Crosswalk

Vehicle Class: Driving Behavior Parameter Set
Default : 4, Footpath (no interaction)

Color:
☐ Invisible

Source: the author, 2009

Figure 4-6 An Example of Link in VISSIM



No.: 13150075 Name: LakeShoreDriveNB
No. of Lanes: 4 Type: 200 Road
Link Length: 90.420 m
Lane width: 3.50 m

Source: the author, 2009

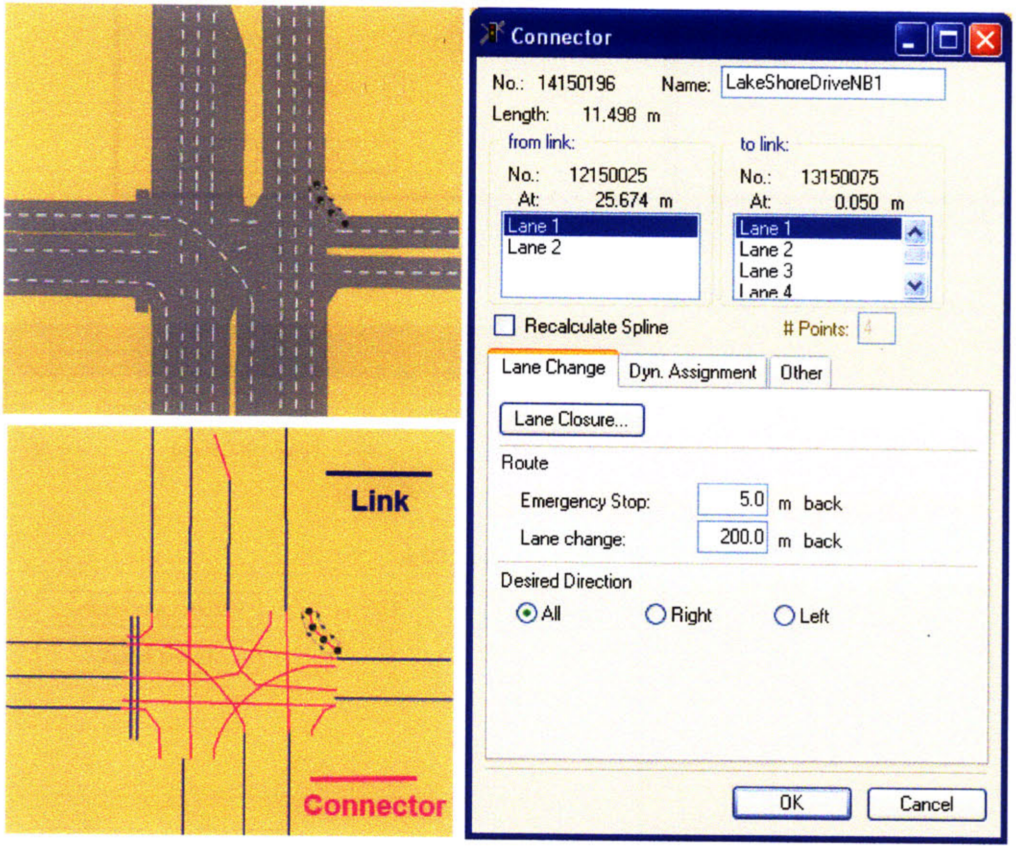
Lanes

Characteristics of lanes can be defined in the *Link Data* module, including the width of each lane of a link. Another important property for the *Lane* module is that it enables lane closure to any pre-defined vehicle class. For example, if we want to have a dedicated bus lane, we may want to close the lane to cars, trucks, and other types of vehicles, while being open to buses. This function is also helpful when there are construction work zones and detours.

Connectors

The representation of intersections requires the use of "link connectors". The reason is that in VISSIM a link cannot serve as a joint or to connect to another link. This link connector serves to join two links. In VISSIM, one of the connector properties allows defining the lane(s) on the "from link" and "to link"; thus it will represent a realistic physical path for traffic flow (see Figure 4-6 or 4-7 for examples). It also allows lane closure to serve similar objectives as discussed previously.

Figure 4-7 An Example of Connector in VISSIM



No.: 14150196 Name: LakeShoreDriveNB1
Length: 11.498 m

from link:
No.: 12150025
At: 25.674 m
Lane 1
Lane 2

to link:
No.: 13150075
At: 0.050 m
Lane 1
Lane 2
Lane 3
Lane 4

☐ Recalculate Spline
Points: 4

Route
Emergency Stop: 5.0 m back
Lane change: 200.0 m back

Desired Direction
● All ○ Right ○ Left

Source: the author, 2009

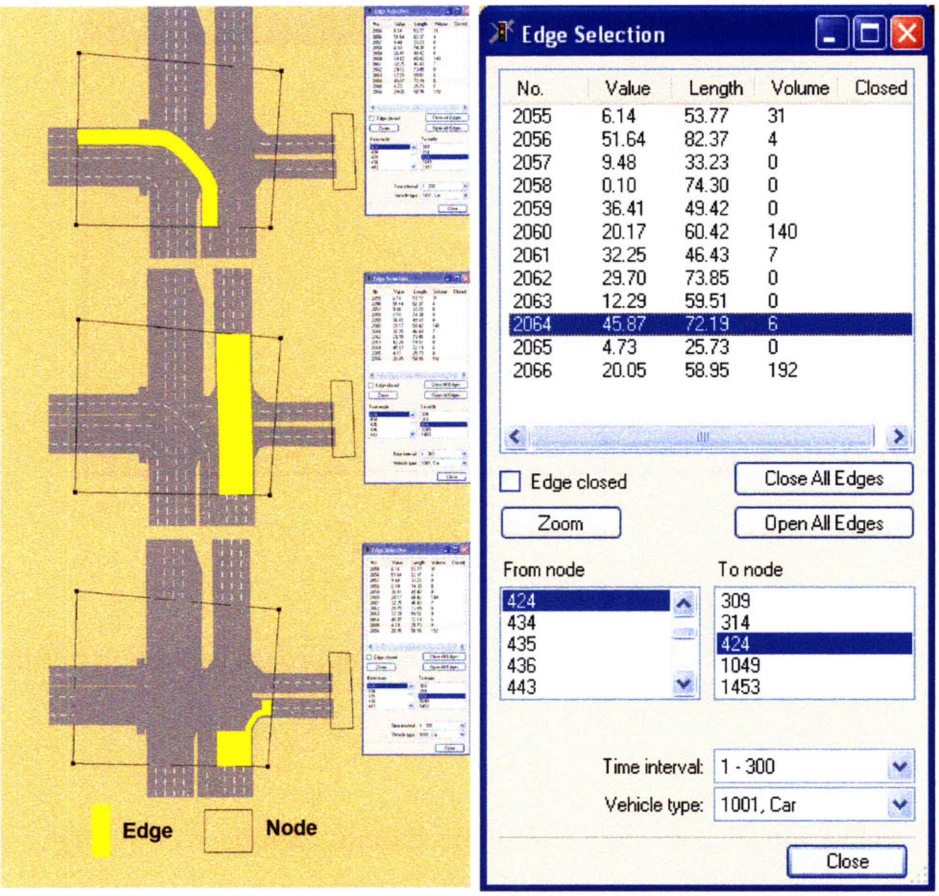
Nodes

Nodes in VISSIM usually represent junctions or intersections in the real world. They also facilitate simplifying the network (see Figure 4-2). Nodes in VISSIM are defined as areas at a junction enclosed by polygons (see Figure 4-7). This simplification of the network will save computing and storage resources.

Edges

Edges in VISSIM are the basic building blocks for routes or paths (see Figure 4-2) in the basic graph theory. Edges in VISSIM are used to build an abstract network graph for the dynamic assignment, which will be introduced later. There can be more than one edge between two nodes, and within a node, edges represent the turning movements, which have a physical length in VISSIM (see an example in Figure 4-8).

Figure 4-8 An Example of Nodes and Edges in VISSIM



No.	Value	Length	Volume	Closed
2055	6.14	53.77	31	
2056	51.64	82.37	4	
2057	9.48	33.23	0	
2058	0.10	74.30	0	
2059	36.41	49.42	0	
2060	20.17	60.42	140	
2061	32.25	46.43	7	
2062	29.70	73.85	0	
2063	12.29	59.51	0	
2064	45.87	72.19	6	
2065	4.73	25.73	0	
2066	20.05	58.95	192	

☐ Edge closed

From node	To node
424	309
434	314
435	424
436	1049
443	1453

Time interval: 1 - 300

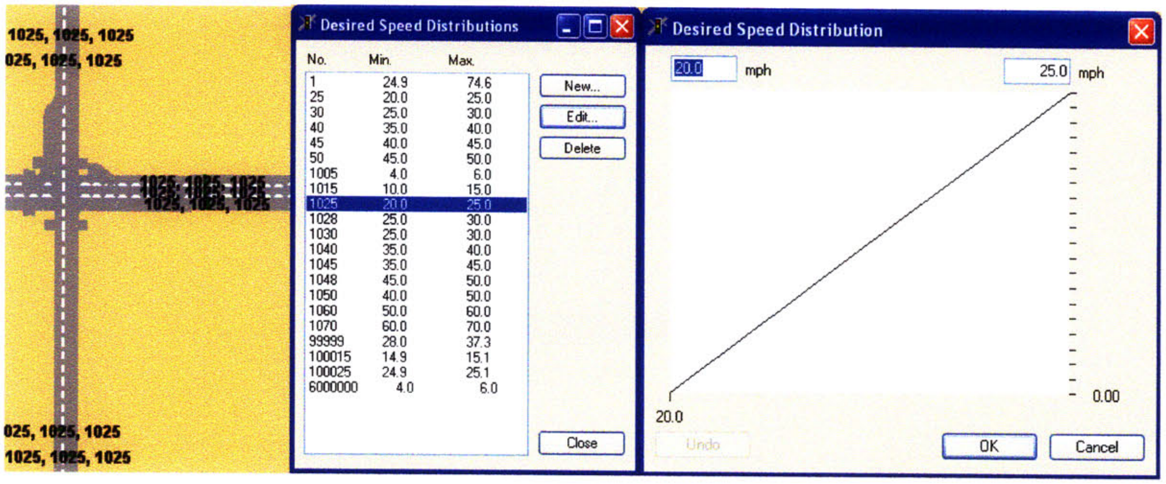
Vehicle type: 1001, Car

Source: the author, 2009

Desired Speed

The desired speed distribution for any vehicle type influences significantly road capacity and achievable travel speeds. Figure 4-9 exemplifies how to set the desired speed parameters, and how it may work. We first need to define the desired speed distribution, and set the location of different desired speed signs on different sections on the road network. A driver in the VISSIM model will follow the desired speed, if not hindered by other vehicles or by signs announcing maximum speeds for a section of the road or street.

Figure 4-9 An Example of Desired Speeds and their Distribution



No.	Min.	Max.
1	24.9	74.6
25	20.0	25.0
30	25.0	30.0
40	35.0	40.0
45	40.0	45.0
50	45.0	50.0
1005	4.0	6.0
1015	10.0	15.0
1025	20.0	25.0
1028	25.0	30.0
1030	25.0	30.0
1040	35.0	40.0
1045	35.0	45.0
1048	45.0	50.0
1050	40.0	50.0
1060	50.0	60.0
1070	60.0	70.0
99999	28.0	37.3
100015	14.9	15.1
100025	24.9	25.1
6000000	4.0	6.0

20.0 mph

25.0 mph

20.0

Source: the author, 2009

4.4.3 *Traffic Control*

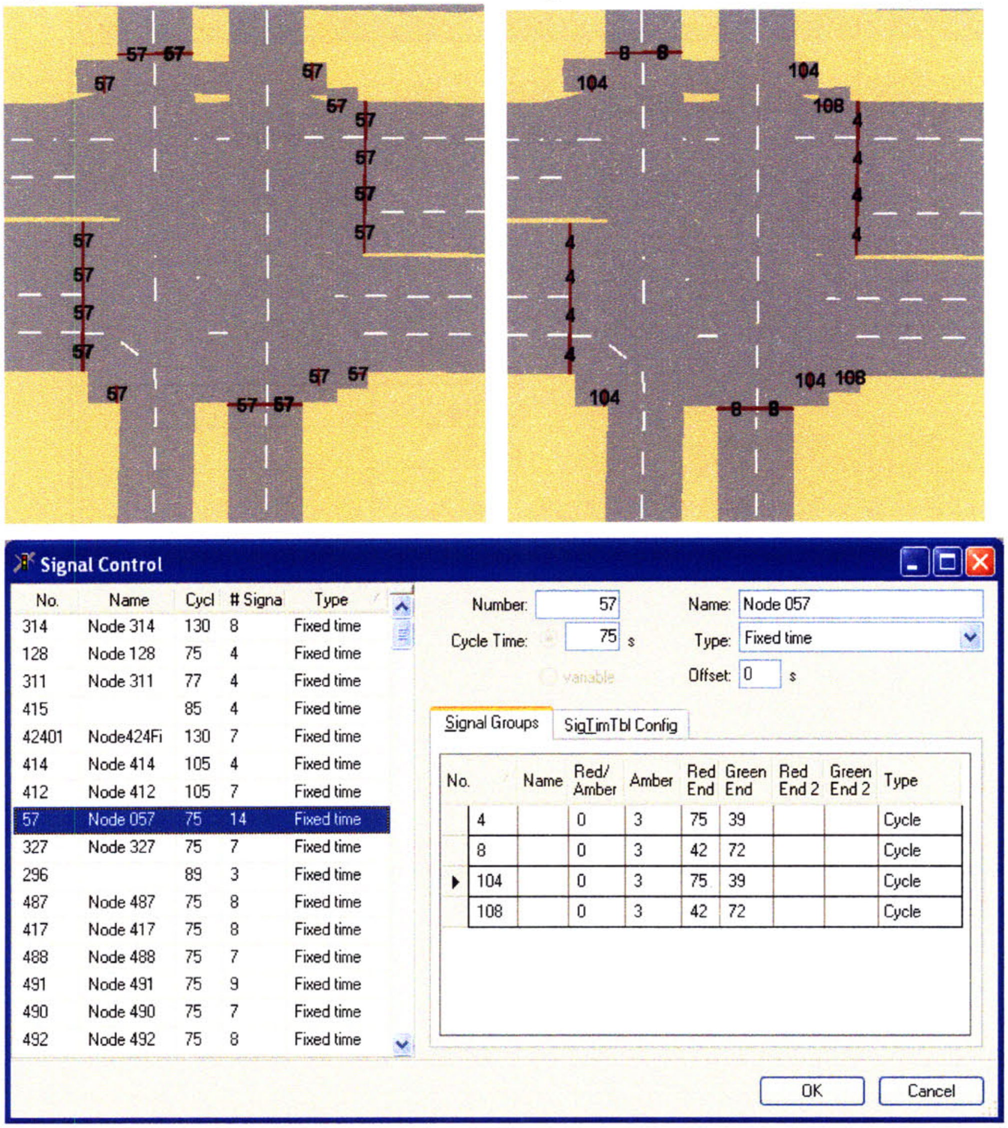
Traffic flows in VISSIM are controlled via two approaches. The first approach is through traffic signal controllers and the other one is through priority rules.

Signal Controllers

In VISSIM traffic signals can be controlled through built-in fixed time controllers, or through external controller interface such as NEMA, with which VISSIM can simulate fully actuated signal control as well as coordinated and semi-actuated coordinated signal control systems.

Fixed-Time Signal Control: With the fixed-time signal controllers, the model starts one signal cycle at the first second, and ends it before the second cycle time. Signal controllers are organized by Signal Controller (SC) Number, and Signal Group (SG) Number. In Figure 4-10, "57" is the Number for SC, and Numbers 4, 8, 104 and 108 are SG numbers. The cycle time for each SG is listed in the Signal Controller editing panel. We can see that for SC 57, the cycle time is 75 seconds. As for SG 4, in a signal cycle, Green starts at second 1, and ends at second 39. There are 3 seconds for Amber, and Red ends at second 75.

Figure 4-10 An Example of Fixed-Time Signal Control Parameter Setting in VISSIM



No.	Name	Cycl	# Signa	Type
314	Node 314	130	8	Fixed time
128	Node 128	75	4	Fixed time
311	Node 311	77	4	Fixed time
415		85	4	Fixed time
42401	Node424Fi	130	7	Fixed time
414	Node 414	105	4	Fixed time
412	Node 412	105	7	Fixed time
57	Node 057	75	14	Fixed time
327	Node 327	75	7	Fixed time
296		89	3	Fixed time
487	Node 487	75	8	Fixed time
417	Node 417	75	8	Fixed time
488	Node 488	75	7	Fixed time
491	Node 491	75	9	Fixed time
490	Node 490	75	7	Fixed time
492	Node 492	75	8	Fixed time

Number: 57

Name: Node 057

Cycle Time: 75 s

Type: Fixed time

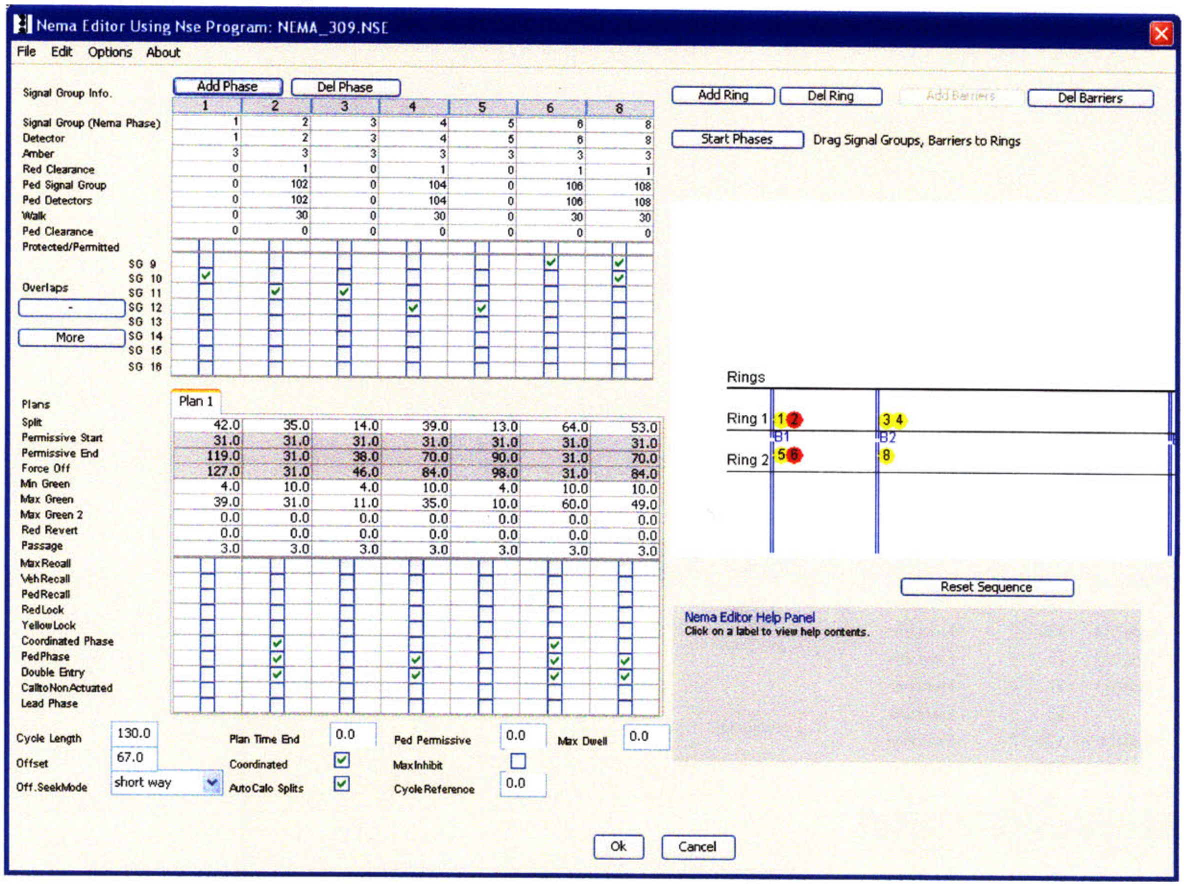
Offset: 0 s

No.	Name	Red/ Amber	Amber	Red End	Green End	Red End 2	Green End 2	Type
4		0	3	75	39			Cycle
8		0	3	42	72			Cycle
104		0	3	75	39			Cycle
108		0	3	42	72			Cycle

Source: the author, 2009

NEMA: During a simulation, VISSIM passes the status of its detectors and signal heads to the NEMA Controller at each simulation second, and the NEMA Controller returns the state of the signal heads for the next simulation second. Each Controller file is saved by the NEMA Editor (NEMA Editor Manual, 2006).

Figure 4-11 An Example of NEMA Editor in VISSIM



Signal Group Info.	1	2	3	4	5	6	8
Signal Group (Nema Phase)	1	2	3	4	5	6	8
Detector	1	2	3	4	5	6	8
Amber	3	3	3	3	3	3	3
Red Clearance	0	1	0	1	0	1	1
Ped Signal Group	0	102	0	104	0	106	108
Ped Detectors	0	102	0	104	0	106	108
Walk	0	30	0	30	0	30	30
Ped Clearance	0	0	0	0	0	0	0
Protected/Permitted	☐	☐	☐	☐	☐	☐	☐
SG 9	☐	☐	☐	☐	☐	☑	☑
SG 10	☑	☐	☐	☐	☐	☐	☑
SG 11	☐	☑	☑	☐	☐	☐	☐
SG 12	☐	☐	☐	☑	☑	☐	☐
SG 13	☐	☐	☐	☐	☐	☐	☐
SG 14	☐	☐	☐	☐	☐	☐	☐
SG 15	☐	☐	☐	☐	☐	☐	☐
SG 16	☐	☐	☐	☐	☐	☐	☐

Plans: Plan 1

	1	2	3	4	5	6	8
Split	42.0	35.0	14.0	39.0	13.0	64.0	53.0
Permissive Start	31.0	31.0	31.0	31.0	31.0	31.0	31.0
Permissive End	119.0	31.0	38.0	70.0	90.0	31.0	70.0
Force Off	127.0	31.0	46.0	84.0	98.0	31.0	84.0
Min Green	4.0	10.0	4.0	10.0	4.0	10.0	10.0
Max Green	39.0	31.0	11.0	35.0	10.0	60.0	49.0
Max Green 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Red Revert	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Passage	3.0	3.0	3.0	3.0	3.0	3.0	3.0
MaxRecall	☐	☐	☐	☐	☐	☐	☐
VehRecall	☐	☐	☐	☐	☐	☐	☐
PedRecall	☐	☐	☐	☐	☐	☐	☐
RedLock	☐	☐	☐	☐	☐	☐	☐
YellowLock	☐	☐	☐	☐	☐	☐	☐
Coordinated Phase	☐	☑	☐	☐	☐	☑	☐
PedPhase	☐	☑	☐	☑	☐	☑	☑
Double Entry	☐	☑	☐	☑	☐	☑	☑
CalltoNonActuated	☐	☐	☐	☐	☐	☐	☐
Lead Phase	☐	☐	☐	☐	☐	☐	☐

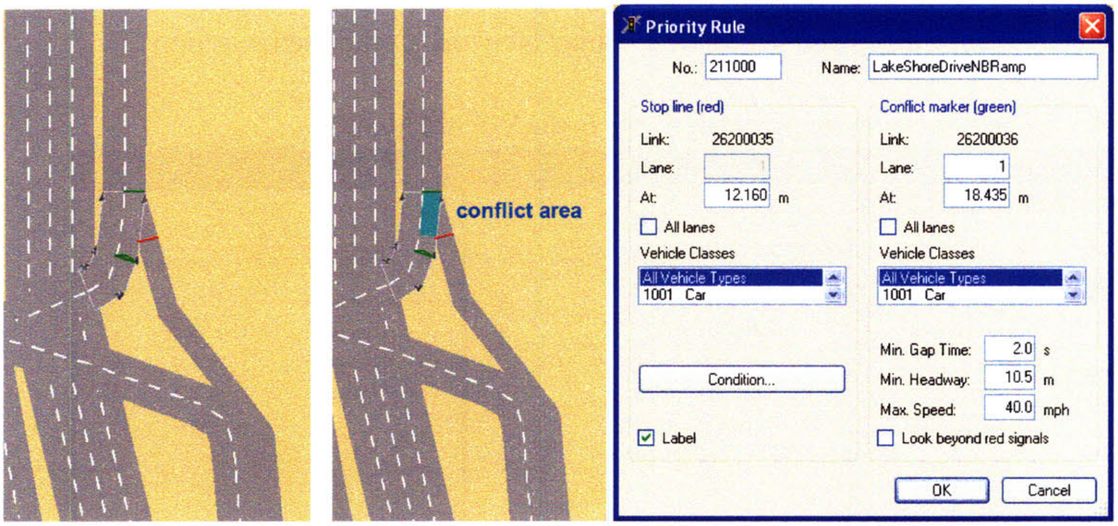
Cycle Length 130.0
Offset 67.0
Off.SeekMode short way
Plan Time End 0.0
Coordinated ☑
AutoCalc Splits ☑
Ped Permissive 0.0
MaxInhibit ☐
CycleReference 0.0
Max Dwell 0.0

Source: the author, 2009

Priority Rules

In VISSIM, the conflicting movements are controlled by priority rules, at non-signalized intersections or at separating or joining links, which apply to all situations where vehicles on different links or connectors will recognize each other. Figure 4-12 demonstrates a basic example of how priority rules may work on a ramp connecting to a highway trunk where there is no signal controller. Figure 4-13 shows the application of priority rules to describe the potential conflicts in an intersection regulated by a signal controller, as not all movements are protected in a given phase, but permitted, thus necessitating of such priority rules.

Figure 4-12 An Example of Priority Rule Settings in VISSIM



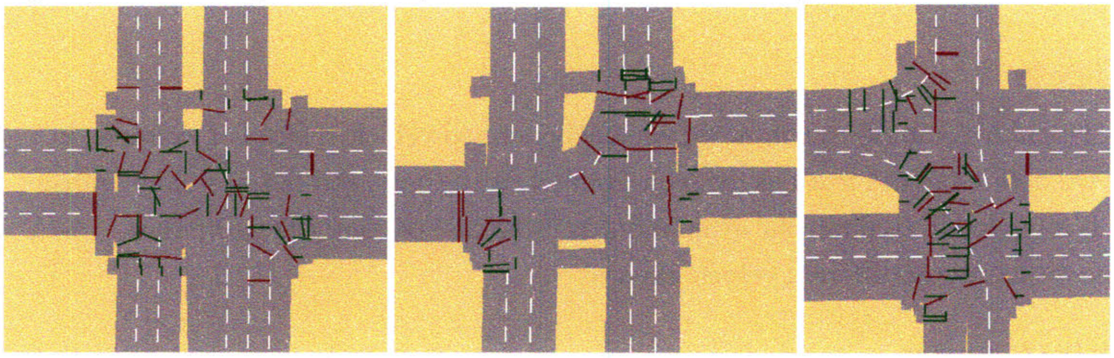
No.: 211000
Name: LakeShoreDriveNBRamp

Stop line (red)
Link: 26200035
Lane: 1
At: 12.160 m
☐ All lanes
Vehicle Classes
All Vehicle Types
1001 Car
☑ Label

Conflict marker (green)
Link: 26200036
Lane: 1
At: 18.435 m
☐ All lanes
Vehicle Classes
All Vehicle Types
1001 Car
Min. Gap Time: 2.0 s
Min. Headway: 10.5 m
Max. Speed: 40.0 mph
☐ Look beyond red signals

Source: the author, 2009

Figure 4-13 Examples of Priority Rules at Intersections with Signal Controllers



Source: the author, 2009

4.4.4 Vehicle Types and Classes

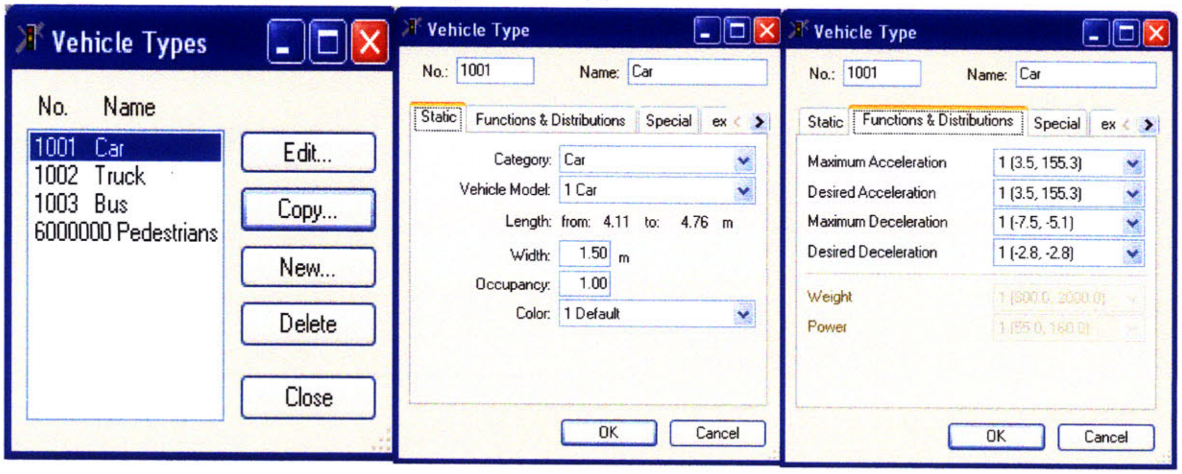
Vehicle Type

Defining vehicle types enables the traffic simulation model to group or differentiate similar or special operating characteristics and physical driving behavior. Typical vehicle types in the VISSIM model include car, truck, bus, tram, bike, and pedestrian. In our Chicago Loop model, we defined vehicle types of car, truck, bus, and pedestrian.

For each vehicle type, we can define the static characteristics such as vehicle length, width, occupancy and color, and also the operational data such as acceleration and deceleration, and driving behavior et cetera. There is a module about special functions for each vehicle type in VISSIM. For example, for bus, we can define the parameters of dwell time model in the PT

Parameters module under the special functions. The specific meanings and calculations about these parameters will be discussed later in the Transit Network Components section.

Figure 4-14 Examples of Defining Vehicle Types in the VISSIM Model



No.	Name
1001	Car
1002	Truck
1003	Bus
6000000	Pedestrians

No.: 1001 Name: Car
Category: Car
Vehicle Model: 1 Car
Length: from: 4.11 to: 4.76 m
Width: 1.50 m
Occupancy: 1.00
Color: 1 Default

No.: 1001 Name: Car
Maximum Acceleration: 1 (3.5, 155.3)
Desired Acceleration: 1 (3.5, 155.3)
Maximum Deceleration: 1 (-7.5, -5.1)
Desired Deceleration: 1 (-2.8, -2.8)
Weight: 1 (800.0, 2000.0)
Power: 1 (55.0, 160.0)

Source: the author, 2009

Vehicle Classes

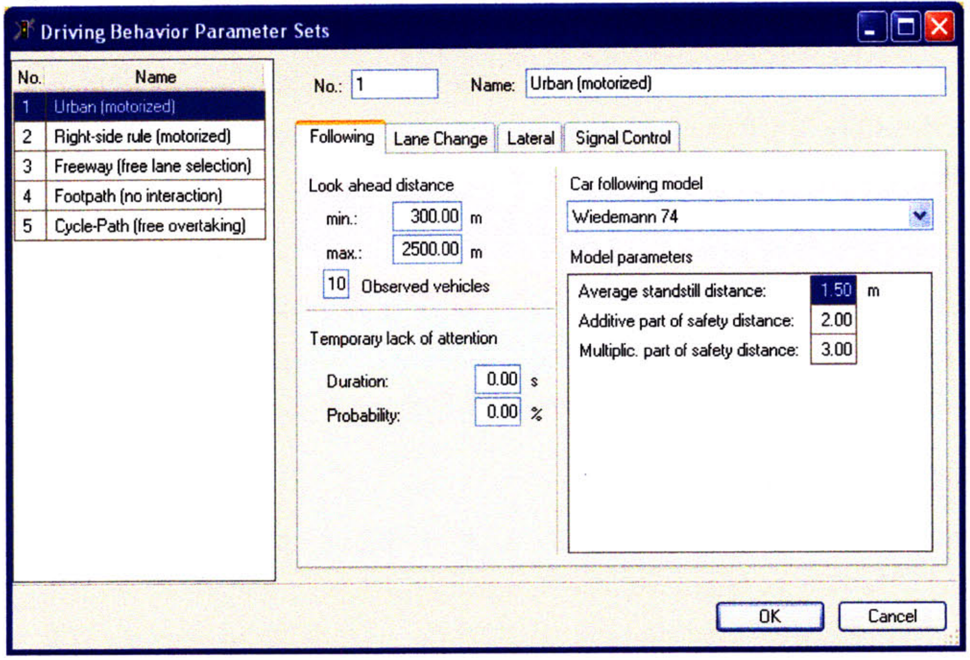
A Vehicle Class may combine one or more previously defined vehicle types. For example, in our model, we define car and truck as the Non-Public Transit Class, and bus as Public Transit Class. This is intended to facilitate the evaluation, as is the case of comparing different performance measures for different vehicle classes.

4.4.5 Driving Behavior

It is claimed that "the traffic flow model in VISSIM is a discrete, stochastic, time step based, microscopic model with driver-vehicle-units as single entities", and that "the (VISSIM) model contains a psycho-physical car following model for longitudinal vehicle movement and a rule-based algorithm for lateral movements" (PTV, 2007).

Figure 4-15 demonstrates the driving behavior sets in VISSIM. Five different types of driving behavior (i.e. Urban, Right-side rule, Freeway, Footpath, and Cycle-Path) have been pre-defined. Within each type, there are four different panel sets--vehicle following behavior, lane change behavior, lateral behavior, and signal control. For more detailed parameter settings, please refer to the VISSIM 4.30 User Manual (PTV, 2007).

Figure 4-15 An Example of Driving Behavior Parameter Setting in VISSIM



No.	Name
1	Urban (motorized)
2	Right-side rule (motorized)
3	Freeway (free lane selection)
4	Footpath (no interaction)
5	Cycle-Path (free overtaking)

No.: 1
Name: Urban (motorized)

Look ahead distance
min.: 300.00 m
max.: 2500.00 m
10 Observed vehicles

Temporary lack of attention
Duration: 0.00 s
Probability: 0.00 %

Car following model: Wiedemann 74

Model parameters
Average standstill distance: 1.50 m
Additive part of safety distance: 2.00
Multiplic. part of safety distance: 3.00

Source: the author, 2009

As mentioned earlier, link type defines the driving behavior on that link. In the Chicago Loop VISSIM Model, we have defined two types of links (see Figure 4-5): the first one is road, whose driving behavior parameter is "urban", and the second one is pedestrian crosswalk, whose driving behavior is "footpath".

4.4.6 Dynamic Traffic Assignment

Definition

In VISSIM, there are two ways to assign traffic. The first one is to use fixed routes, which are fixed sequences of links and connectors. The other one is to use dynamic traffic assignment (DTA) algorithm. The Federal Highway Administration[1] defines dynamic traffic assignment as using "expert computer processing to develop Traffic Estimation and Prediction Systems (TrEPS) that predict where and when drivers travel on the road network."

The main difference of DTA to static assignments is that the location of every vehicle is monitored in time and space along each simulation step, as it proceeds from its origin to its destination. On the other hand, DTA does not exceed the link or intersection capacity and it replicates the upstream propagation of spill-back from a congestion point.

---

[1] See http://ops.fhwa.dot.gov/trafficanalysistools/dta.htm

In a fixed route assignment, the model describes the situation in which drivers do not have choices to change sequences of links, and they have to follow pre-defined routes. However, in a dynamic traffic assignment, the path choice during the assignment of an auto matrix follows a logit model based on a disutility function which contains time, length, tolls and any other road feature capable of influencing pathing.

Advantages

One of the advantages of dynamic traffic assignment over static route, including conventional algorithms like User Equilibrium, is that congested conditions are represented in a more realistic way, and that other road and user factors are similarly closer to reality..

Assignment Methods in this Study

Two separate transport systems, one is for automobiles, and the other for bus transit are considered in our model. The one for buses will use static route assignment method, since it corresponds to a fixed route, schedule base, and transport mode. As for automobiles, we will employ dynamic traffic assignment (DTA) for the Loop VISSIM model. DTA will enable us to understand how drivers will change route choices at the micro level, and how bus improvements will leverage the general automobile traffic at the macro level.

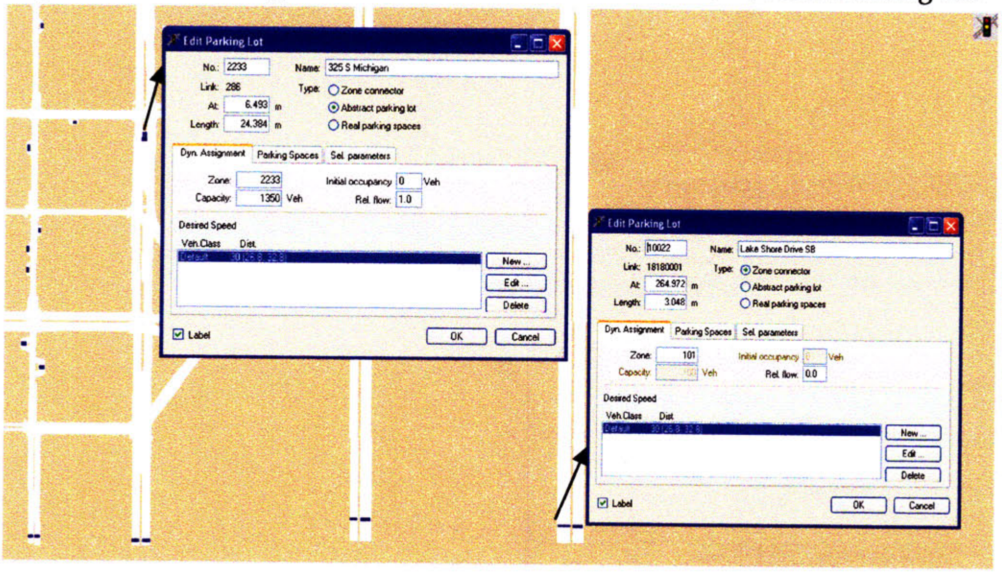
4.4.7 Parking Lots

The concept of parking as the sinks and sources of auto traffic in VISSIM relies on either static routes or dynamic traffic assignment (DTA). Since we will use DTA method in this study, two types of parking lots for the Chicago VISSIM model are defined: 1) zone connector, and 2) abstract parking lot.

Zone Connector

Zone connectors in VISSIM represent the links serving as origins and destinations where traffic enters or exits a network. The capacity of this kind of parking lots is not restricted, and no vehicle needs to slow down when being removed from the network. There is the "Type" option in the VISSIM parking lot module. While creating a parking lot, one can define the type as "Zone connecter" if it is not an existing parking lot, but rather just an origin or destination in the network (See Figure 4-16).

Figure 4-16 Parking Lots in VISSIM: Zone Connector & Abstract Parking Lot



Edit Parking Lot
No.: 2233 Name: 325 S Michigan
Link: 286 Type: ○ Zone connector
At: 6.493 m ● Abstract parking lot
Length: 24.384 m ○ Real parking spaces
Dyn. Assignment | Parking Spaces | Sel. parameters
Zone: 2233 Initial occupancy: 0 Veh
Capacity: 1350 Veh Rel. flow: 1.0
Desired Speed
Veh.Class Dist.
Default 30 (26.8, 32.8)
☑ Label

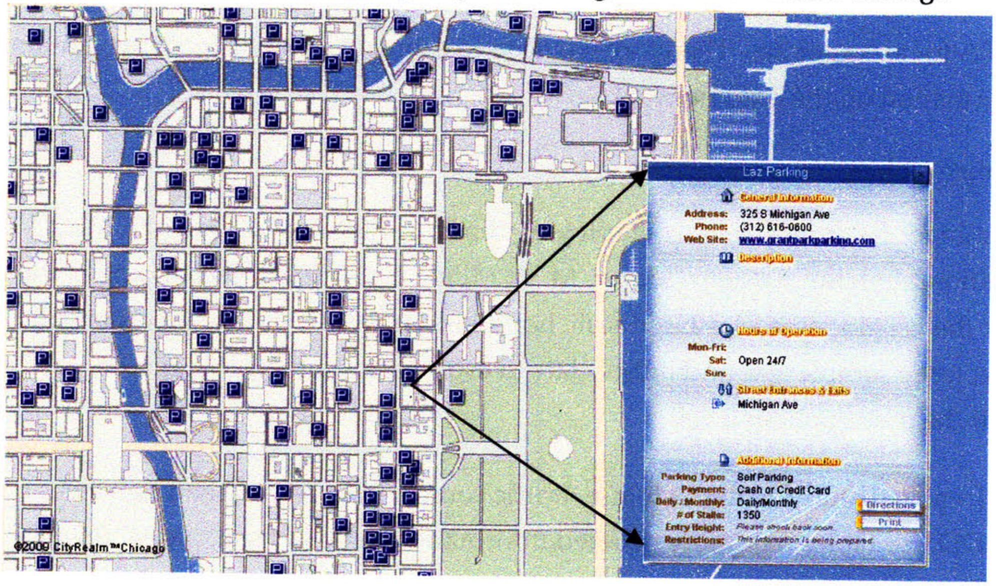
Edit Parking Lot
No.: 10022 Name: Lake Shore Drive SB
Link: 18180001 Type: ● Zone connector
At: 264.972 m ○ Abstract parking lot
Length: 3.048 m ○ Real parking spaces
Dyn. Assignment | Parking Spaces | Sel. parameters
Zone: 101 Initial occupancy: 0 Veh
Capacity: [illegible] Veh Rel. flow: 0.0
Desired Speed
Veh.Class Dist.
Default 30 (26.8, 32.8)
☑ Label

Source: the author, 2009

Abstract Parking Lot

Abstract parking lots in VISSIM are used to represent real-world parking facilities. Parking lots in the Chicago Central Business District (see Figure 4-17) mainly serve as destinations during AM Peak hours and origins for PM Peak hours. In the VISSIM model, each parking lot's accurate location (including its exits and entrances locations) and its capacity need to be defined (see Figure 4-16 & Figure 4-18).

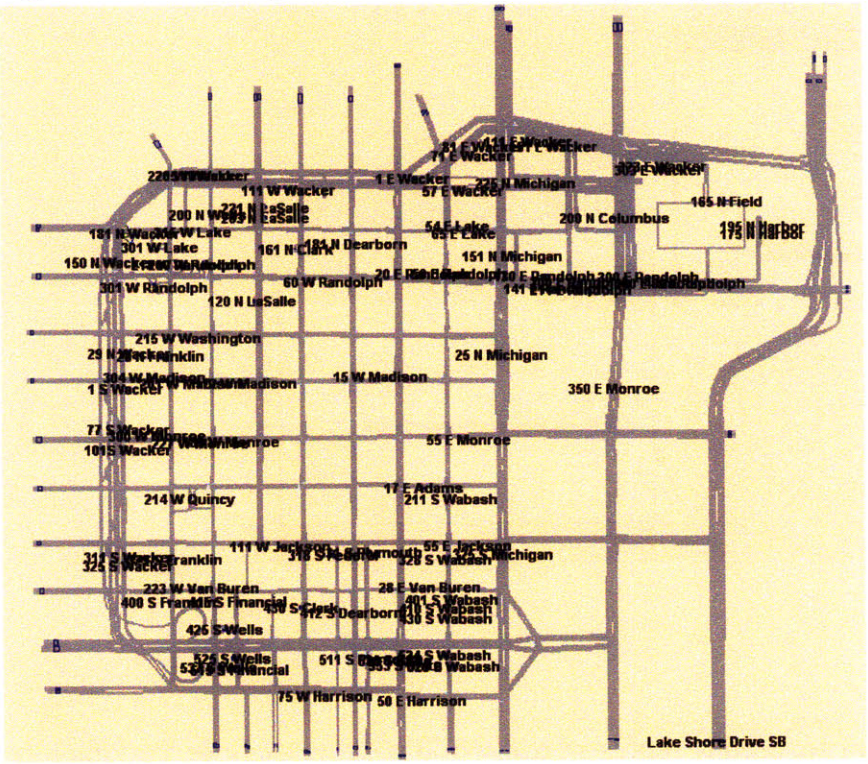
Figure 4-17 Locations and Capacity of Parking Lots in Downtown Chicago



Laz Parking
General Information
Address: 325 S Michigan Ave
Phone: (312) 616-0600
Web Site: www.grantparkparking.com
Description
Hours of Operation
Mon-Fri:
Sat: Open 24/7
Sun:
Street Entrances & Exits
Michigan Ave
Additional Information
Parking Type: Self Parking
Payment: Cash or Credit Card
Daily / Monthly: Daily/Monthly
# of Stalls: 1350
Entry Height: Please check back soon.
Restrictions: This information is being prepared.

Source: the Parking Industry Labor Management Council, 2008. Retrieved January 20, 2009, from http://www.chicagoparkingmap.com/map_static.jsp

Figure 4-18 Parking Lot Locations in the Chicago Loop VISSIM Model



Source: the author, 2009

4.4.8 *Travel Demand: Origin-Destination Matrix*

An origin-destination (O-D) matrix is a trip table which provides information of traffic flows for each origin and destination pair. OD matrices are the basis for dynamic traffic assignment (DTA). Since buses have static routes and schedules, we will use fixed route assignment for buses, and apply DTA for automobiles. Therefore we need to estimate OD matrices that contain the vehicle flow information on the road network.

OD Estimation Approaches

Traditionally, OD estimation is conducted by employing the Four-Step Travel Demand Model or Urban Transportation Modeling System (Meyer, M., & Miller, E., 2000). However, one of the important inputs for the UTMS method is large scale household travel survey, which is usually very expensive to get large sample size and out-of-date to estimate a synthetic Origin-Destination matrix at the metropolitan level.

An alternative for a localized study as this is to use, traffic counts observed on road networks to estimate up-to-date OD trip tables. For more detailed information in this aspect, please refer to Turnquist & Gur (1979), Yang, et al (1992), and Ashok (1996).

OD Estimation by TransCAD

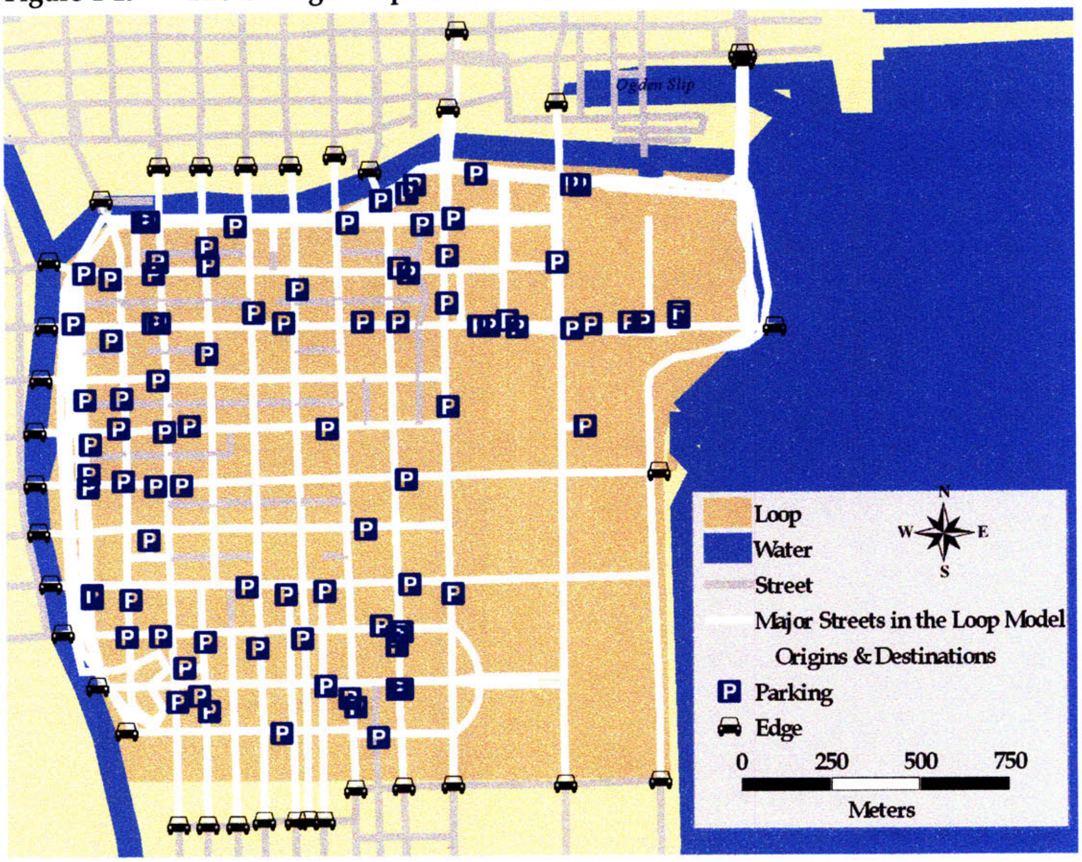
TransCAD is a GIS for Transportation modeling package developed by Caliper Corporation. It provides: 1) a GIS engine with special extensions for transportation; 2) mapping, visualization, and analysis tools designed for transportation applications; and 3) application modules for routing, travel demand forecasting, public transit, logistics, site location, and territory management (Caliper, 2002).

TransCAD also incorporates an OD estimation procedure (as demonstrated in Figure 4-1) to estimate/update OD matrices based on sample traffic counts and initial base trip tables (Caliper, 2002).

a). Data Input: Network Components

In order to apply the TransCAD OD estimation procedure for automobiles, we prepared a TransCAD model, containing the same network elements (e.g. links, locations of origins and destinations/parking lots, etc) as in the Chicago Loop VISSIM model (see Figure 4-19).

Figure 4-19 The Chicago Loop TransCAD Model



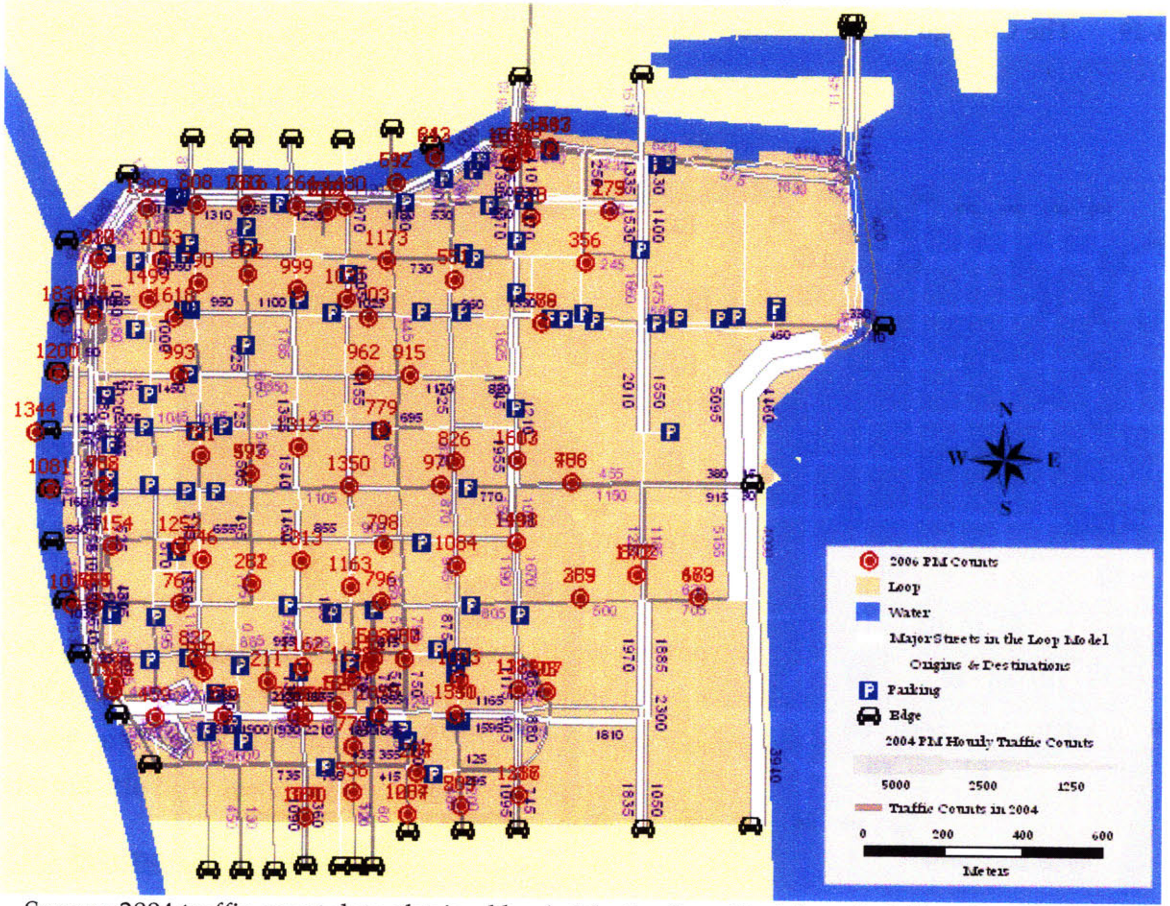
Source: data obtained by A. Martin from the Mayor's Office, the City of Chicago, 2004; mapped by the author, 2008.

The key properties of the network elements to estimate the OD matrix are: 1) travel time (calculated from travel speeds and length of links), 2) link capacity, and 3) traffic counts. The value of travel speeds and link capacity are the same as those in the VISSIM model, although it does not represent the intersection controllers.

b). Data Input: Traffic Counts

Two sets of traffic counts data were used for estimating/updating the PM peak hour automobile OD matrix. The first set of traffic counts data was obtained by Ajay Martin, a previous MIT graduate student who worked as an intern in the Mayor's Office at the City of Chicago in year 2004. The author obtained a second set of traffic counts, which was the up-to-date traffic counts data provided by the Office of Emergency Management & Communication, City of Chicago. Since the first data set had a wider coverage of links in Chicago downtown, it was used to estimate an initial OD trip table. As the second data set is most up-to-date, and has a smaller sample, it was used to update the initial base trip table.

Figure 4-20 PM Peak Hourly Traffic Counts in Chicago Loop, 2004



Source: 2004 traffic count data obtained by A. Martin, from the Mayor's Office, City of Chicago, 2004; 2006 traffic count data obtained by the author from OEMC, Chicago, 2006; mapped by the author, 2009.

c). Data Input: A Base OD Trip Table

In order to estimate an accurate origin-destination (OD) matrix by TransCAD, we created a synthetic OD trip table (or seed OD matrix), which provides a starting point for OD estimation. This initial OD matrix was generated based on the following steps, mimicking the first and second steps of a traditional Four-Step Model:

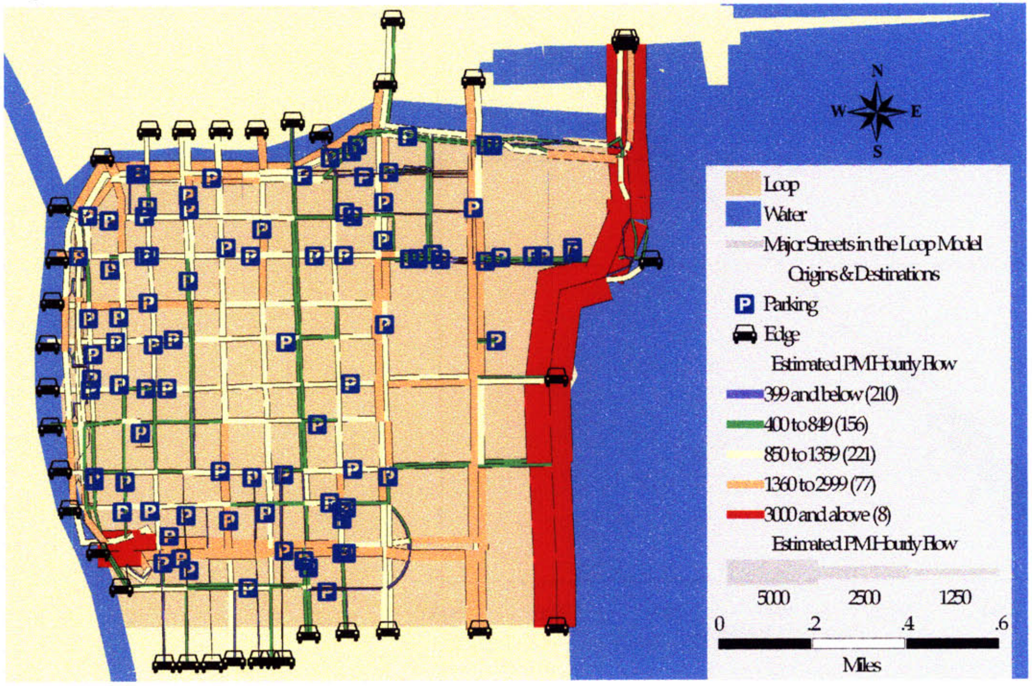
- Define the total auto trips produced as equal to the total auto trips attracted by using a scaling factor.
- Establish parking-lot flow assumption (for PM peak)
- Assume that production equals to one third of parking capacity (for PM peak)
- Assume that attraction equals to seven percent of parking capacity (for PM peak)

By employing a series of Matlab programs (see Appendix A), a seed OD matrix (size: 127 by 127) was generated.

d). OD Estimation Output

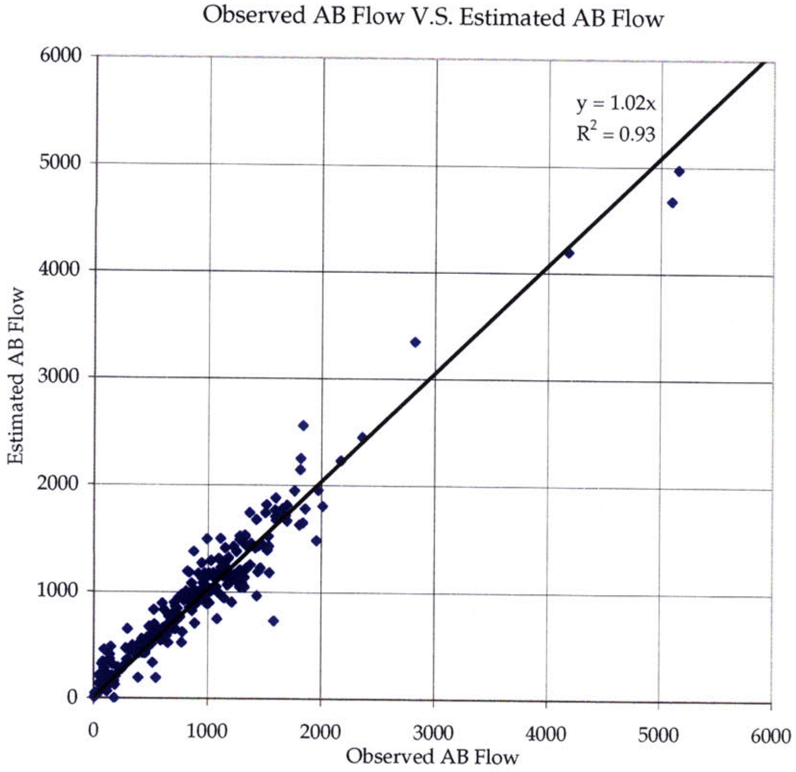
After the several iterations of OD estimation by TransCAD, we obtained the following results, which fit observed and assigned link flows.

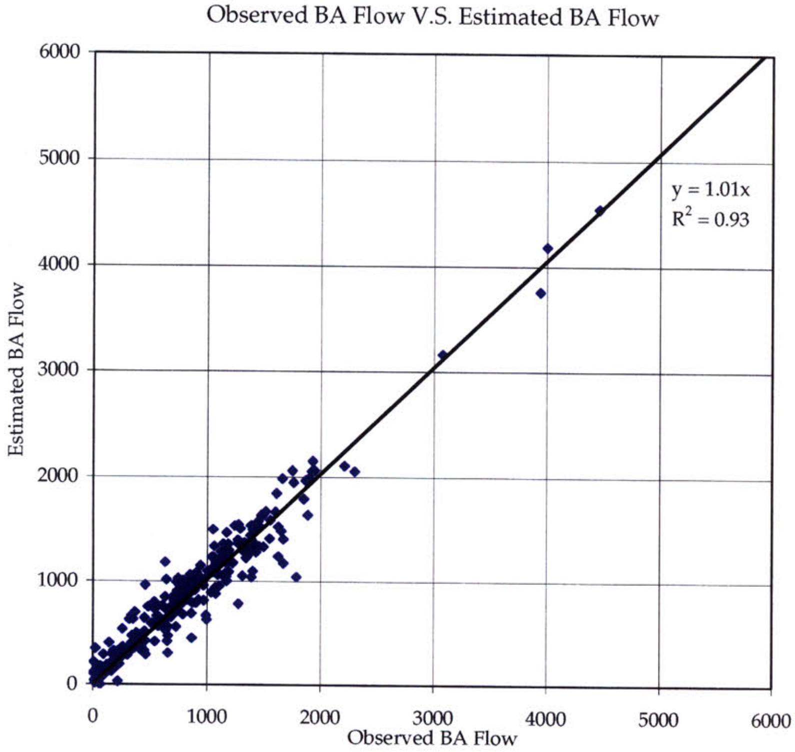
Figure 4-21 Estimated Link Volume by TransCAD



Source: the author, 2009

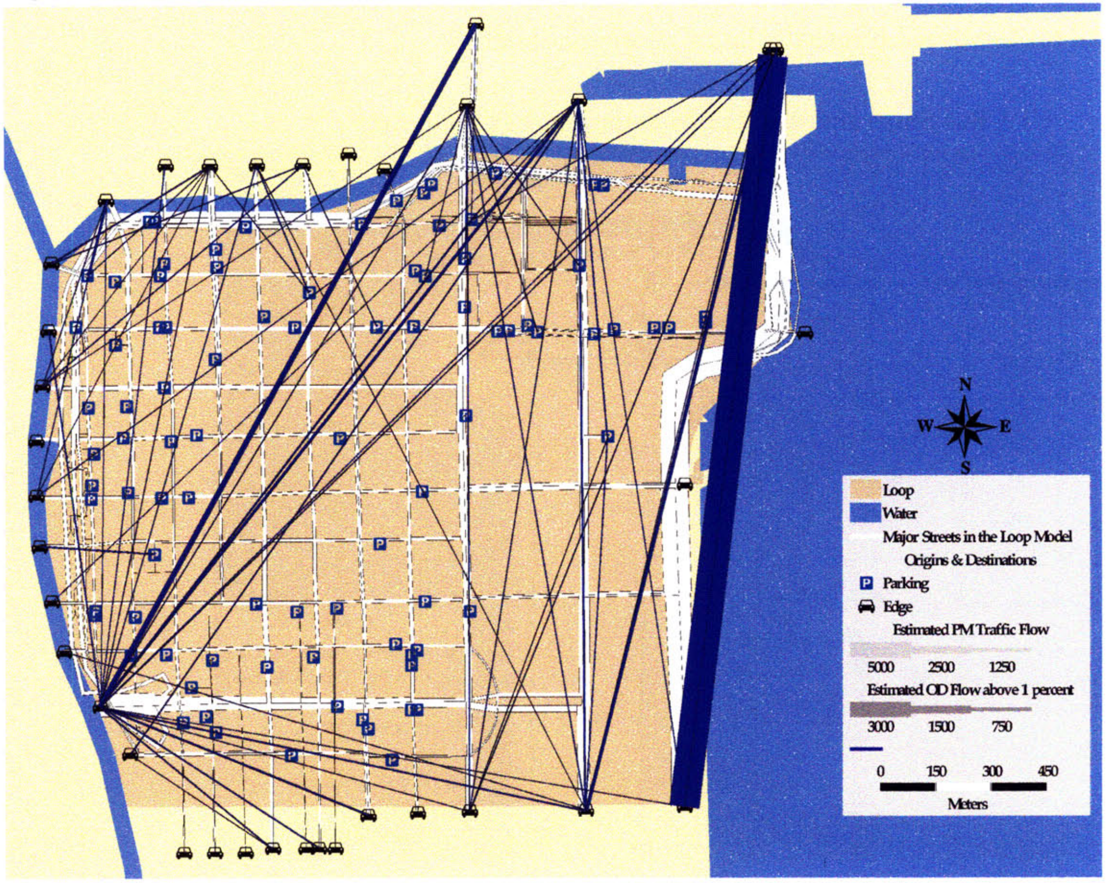
Figure 4-22 Observed v.s. Estimated Link Flow by Using TransCAD





Source: the author, 2009

Figure 4-23 Automobile OD Matrix Estimation by using TransCAD



Source: the author, 2009

According to Figure 4-22, we can see that the estimation of the hourly link flow is very close to the observed hourly traffic counts. After running an initial traffic simulation by VISSIM, it is necessary to evaluate, and re-estimate the OD matrix by comparing and updating the network capacity, traffic signals and road counts, and traffic flows to calibrate the base VISSIM simulation model.

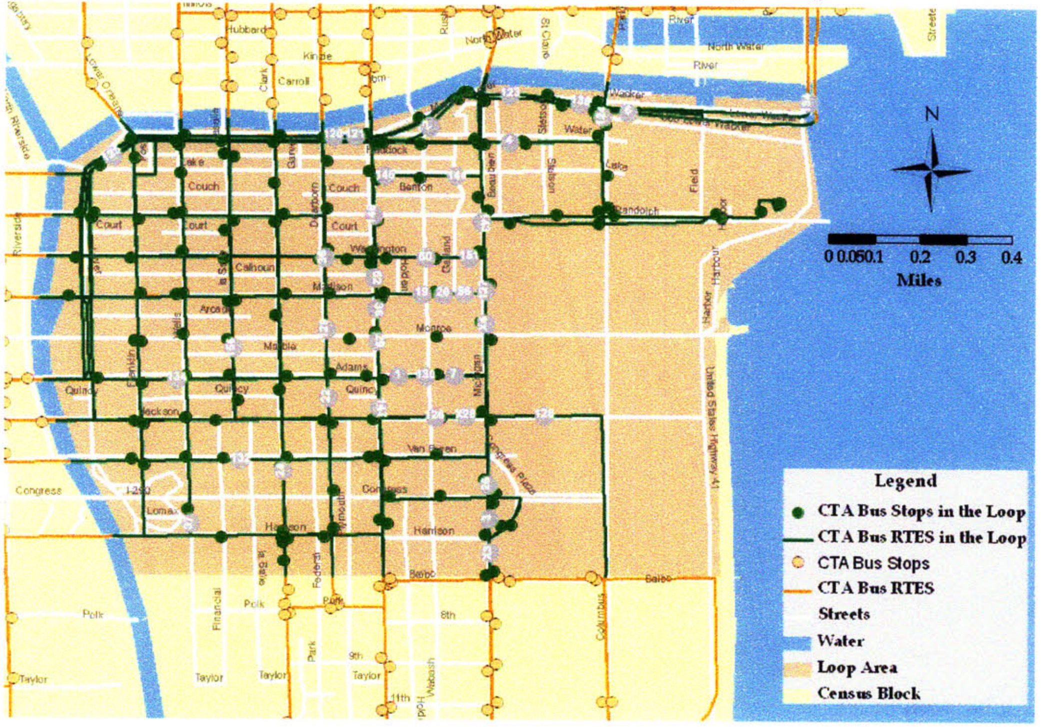
4.4.9 Bus Transit Network Components

Bus Stops

Out of a total 12,180 CTA bus stops in the City of Chicago, 156 of them are located in the Loop Area as defined previously. Figure 4-24 represents the locations of these CTA bus stops as well as the bus routes serving the Loop Area.

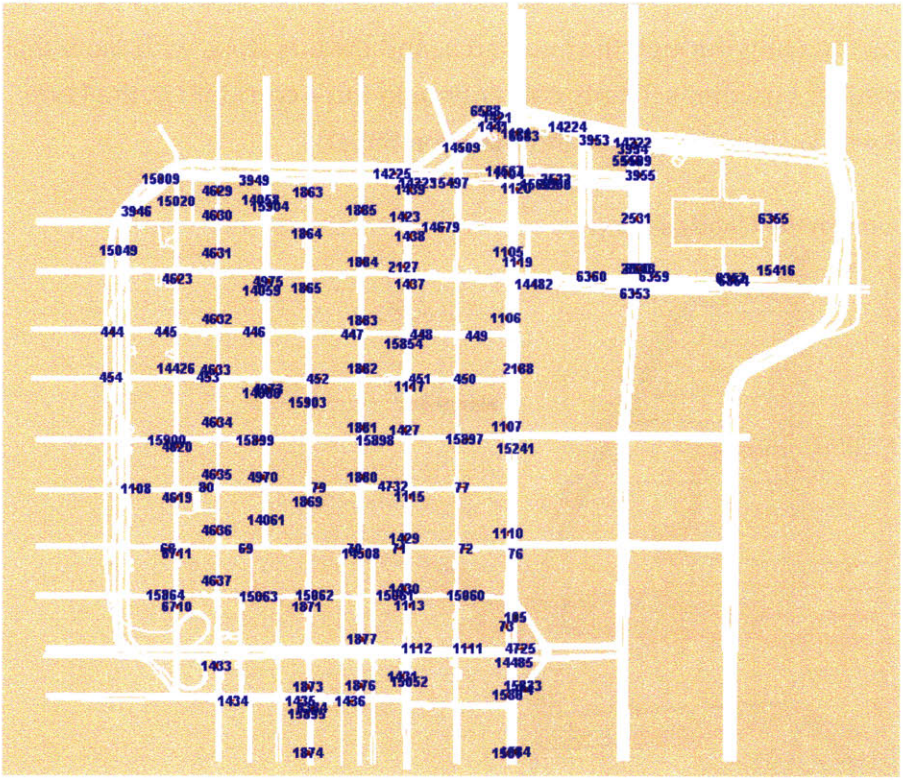
In the VISSIM model, we have defined the location of these bus stops with their ID number, name, length, and lane position (see Figure 4-25). More importantly, we can define the number of hourly boarding passengers at the stop level for each stop-route pair (see Figure 4-26), which is very useful for the dwell time calculation discussed later.

Figure 4-24 CTA Bus Stops and Bus Routes in the Chicago Loop Area



Source: GIS data obtained from the CTA, 2007; mapped by the author, 2008

Figure 4-25 Bus Stop Representations in the VISSIM Model



Source: the author, 2009

Figure 4-26 Examples of Bus Stop Parameters in the VISSIM Model

Transit Stops: 148

No.	Name
446	Washington and LaSalle EB
447	Washington and Dearborn EB
448	Washington and State EB
449	Washington and Wabash EB
450	Madison and Wabash WB
451	Madison and State WB
452	Madison and Clark WB
453	Madison and Wells WB
454	Madison and Wacker WB
1104	Michigan and South Water SB
1105	Michigan and Randolph SB
1106	Michigan and Washington SB
1107	Michigan and Monroe SB
1108	Adams and Wacker WB
1110	Michigan and Jackson SB
1111	Congress and Wabash WB
1112	Congress and State WB
1113	State and Van Buren NB
1115	State and Adams NB
1117	State and Madison NB
1119	Michigan and Randolph NB
1120	Michigan and South Water NB
1121	Michigan and Wacker
1421	Wacker and Michigan WB
1423	State and Lake SB
1427	State and Monroe SB
1429	State and Jackson SB
1430	State and Van Buren SB
1431	State and Congress SB
1433	Wells and Congress SB
1434	Harrison and Financial EB
1435	Harrison and Clark EB
1436	Harrison and Dearborn EB

Edit bus/tram stop

No.: 1105
Name: Michigan and Randolph SB
Length: 11.629 m
Type: ● Street ○ Lay-by
Link: 12150007
Lane: 1
At: 9.144 m
☑ Label

Boarding Passengers

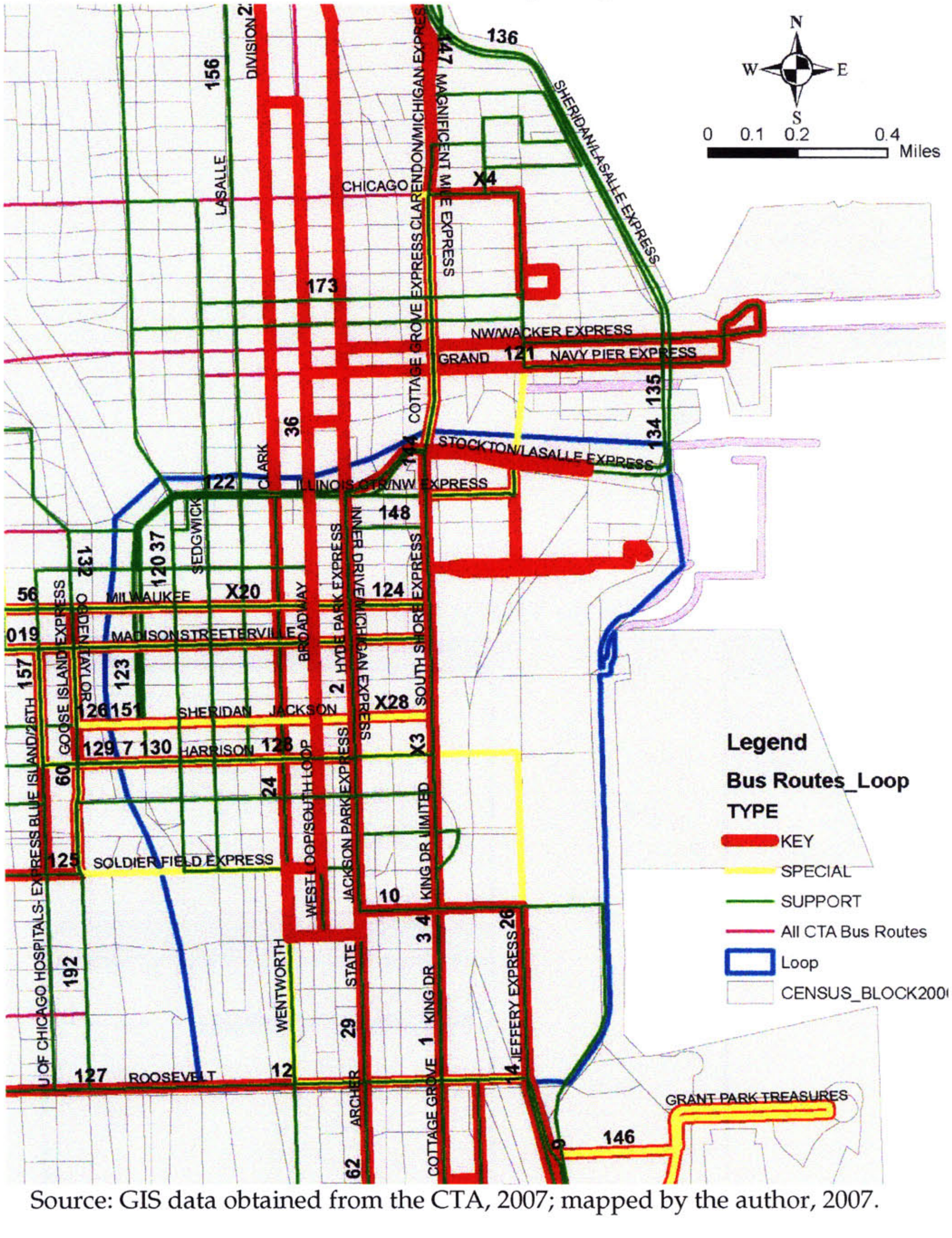
Pers./h	from	until	Line(s)
26	0	99999	302
19	0	99999	304
57	0	99999	402
38	0	99999	404
32	0	99999	2602
8	0	99999	12402
5	0	99999	14502
3	0	99999	14702
15	0	99999	15102
9	0	99999	15702

Source: the author, 2009

Bus Routes

There are 47 CTA bus routes traveling through the Loop area, and the bus stops with more than 7500 average weekday passenger boardings mainly concentrate in three corridors in the Loop area (including Michigan Ave, Washington Street, and Madison Street)

Figure 4-27 **CTA Bus Routes in the Chicago Loop**



Source: GIS data obtained from the CTA, 2007; mapped by the author, 2007.

Bus Schedule and Service Rate

Table 4-3 CTA Bus Routes in the Chicago Loop

CNT	ROUTE	NAME	TYPE	OWL
1	151	SHERIDAN	KEY	0
2	20	MADISON	KEY	1
3	22	CLARK	KEY	1
4	29	STATE	KEY	0
5	3	KING DR	KEY	0
6	36	BROADWAY	KEY	0
7	4	COTTAGE GROVE	KEY	0
8	6	JACKSON PARK EXPRESS	KEY	0
9	60	BLUE ISLAND/26TH	KEY	1
10	62	ARCHER	KEY	1
11	124	NAVY PIER EXPRESS	SPECIAL	0
12	128	SOLDIER FIELD EXPRESS	SPECIAL	0
13	19	STADIUM EXPRESS	SPECIAL	0
14	1	INDIANA/HYDE PARK	SUPPORT	0
15	10	MUSEUM OF SCIENCE & INDUSTRY	SUPPORT	0
16	120	NW/WACKER EXPRESS	SUPPORT	0
17	121	UNION/WACKER EXPRESS	SUPPORT	0
18	122	ILLINOIS CTR/NW EXPRESS	SUPPORT	0
19	123	ILLINOIS/UNION EXPRESS	SUPPORT	0
20	125	WATER TOWER EXPRESS	SUPPORT	0
21	126	JACKSON	SUPPORT	0
22	127	MADISON/ROOSEVELT CIRCULATOR	SUPPORT	0
23	129	WEST LOOP/SOUTH LOOP	SUPPORT	0
24	132	GOOSE ISLAND EXPRESS	SUPPORT	0
25	134	STOCKTON/LASALLE EXPRESS	SUPPORT	0
26	135	CLARENDON/LASALLE EXPRESS	SUPPORT	0
27	136	SHERIDAN/LASALLE EXPRESS	SUPPORT	0
28	14	JEFFERY EXPRESS	SUPPORT	0
29	143	STOCKTON/MICHIGAN EXPRESS	SUPPORT	0
30	144	MARINE/MICHIGAN EXPRESS	SUPPORT	0
31	145	WILSON/MICHIGAN EXPRESS	SUPPORT	0
32	146	INNER DRIVE/MICHIGAN EXPRESS	SUPPORT	0
33	147	OUTER DRIVE EXPRESS	SUPPORT	0
34	148	CLARENDON/MICHIGAN EXPRESS	SUPPORT	0
35	156	LASALLE	SUPPORT	0
36	157	STREETERVILLE	SUPPORT	0
37	173	U OF C - LAKE VIEW EXPRESS	SUPPORT	0
38	192	U OF CHICAGO HOSPITALS- EXPRESS	SUPPORT	0
39	2	HYDE PARK EXPRESS	SUPPORT	0
40	24	WENTWORTH	SUPPORT	0
41	26	SOUTH SHORE EXPRESS	SUPPORT	0
42	56	MILWAUKEE	SUPPORT	0
43	7	HARRISON	SUPPORT	0
44	X20	WASHINGTON/MADISON EXPRESS	SUPPORT	0
45	X28	STONY ISLAND EXPRESS	SUPPORT	0
46	X3	KING DR LIMITED	SUPPORT	0
47	X4	COTTAGE GROVE EXPRESS	SUPPORT	0

Source: the CTA, 2007

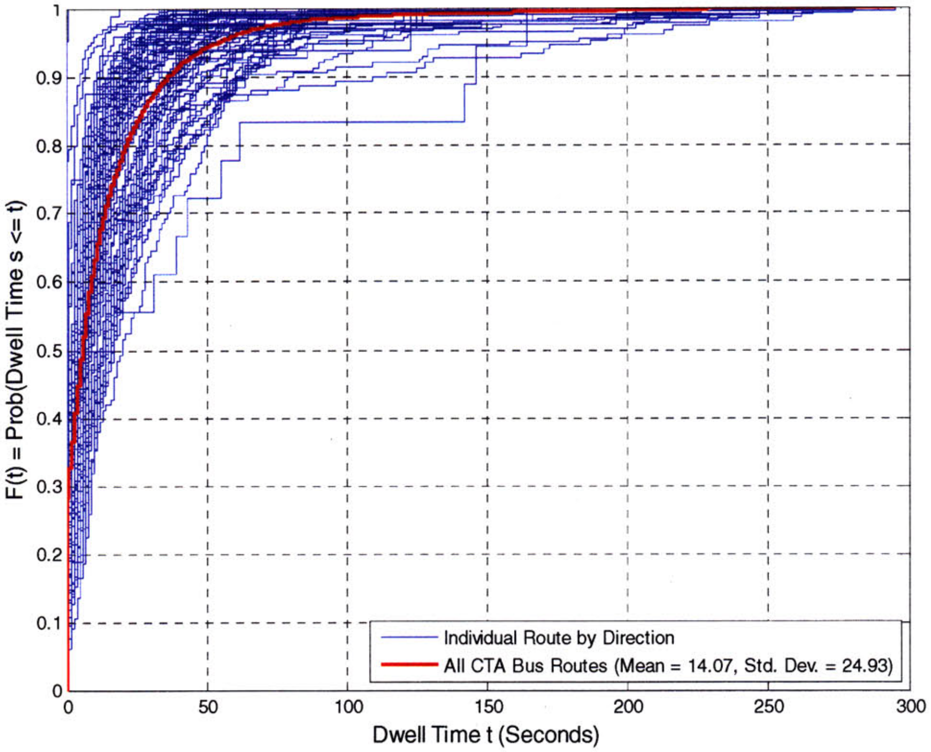
4.4.10 Bus Dwell Time

There are two methods to model transit vehicle dwell times in VISSIM: 1) dwell time distributions, and 2) dwell time calculation using a pre-defined dwell time model. Both methods have their pros and cons, as we will discuss them later. For the Loop VISSIM model, we chose Option 2, and estimated a dwell time model.

Bus Dwell Time Distribution

There are two types of distribution to estimate dwell times in the VISSIM model: 1) normal distribution, and 2) empirical distribution. The latter one needs more data. Thanks to the richness of the CTA bus activity historical records, we could derive empirical dwell time distributions for all the buses traveling through our study area, the Loop, during PM peak. The author queried the bus history data during the PM peak hours (16:30 to 18:00) on weekdays in the first week of April in 2007 from the CTA AVAS database, and estimated empirical dwell time distributions for different directions (i.e. inbound and outbound) for each bus route(see Appendix B). Figure 4-28 shows the empirical dwell time cumulative distribution functions (CDFs) for all the bus routes traveling through the Loop area.

Figure 4-28 Empirical Dwell Time CDF s for Bus Routes Traveling through the Loop



Source: data obtained from the CTA AVAS database, 2009; analyzed by the author, 2008

There are several shortcomings with the empirical distribution functions when used for defining the dwell times in the VISSIM model:

- It cannot replicate accurate bus stopping behavior at particular stops, such as possible clustering of bus vehicles. The reason is that it cannot estimate how such a clustering will redistribute boardings and alightings, based on an hourly demand along that direction.
- Since the dwell times used to determine the cumulative distribution functions are derived from the bus historical data, they already incorporate all the possible physical and human factors that determine them. However, we decided to separate these factors and quantify them so that we could model the changes of dwell time induced by changes in these factors, such as the changes of dwell time due to bus stop location changes (which will reduce the effects of bus clustering or bus pile-ups).

An Econometric Bus Dwell Time Model

In order to avoid the aforementioned shortcomings of the first model, and represent accurately the bus dwell times in the VISSIM model, we developed a bus dwell time model based on the same data set described previously. Due to computational capacity and time constraints, bus history data in the first 5 days of April 2007 were selected to estimate the dwell time model. A larger amount of data for different months and years could be obtained; however, the author found that the estimation results were accurate enough when compared to the results of a previous dwell time model developed by Milkovits (2008).

In Milkovits' bus dwell time model for the CTA (2008), he included several variables such as passenger demand, onboard crowding, passenger alighting door choices, passenger ticketing media type, and bus types. However, since VISSIM has a pre-defined dwell time model, which only accounts for influences of the number of passenger boardings, the number of passenger alighting and door clearance, this thesis only indentified the number of boardings and alightings plus a constant to estimate the parameters for dwell times in the VISSIM model.

$\text{Dwell time} = \alpha + \beta_1 * \text{FOn} + \beta_2 * \text{MixedOff} + \varepsilon$

Where:

Dwell time is defined as the time interval between the first door opening and the last door closing.

Fon is the number of front-door boardings;

MixedOff is the total number of front-door and rear door alightings.

α is a constant, which can be explained as door clearance duration.

Coefficients β_1 and β_2 can be understood as the unit time that each passenger needs to board or alight.

ε is an error term that includes all other unobserved factors that influence the dwell time.

Table 4-4 Variables for the Dwell Time Model for VISSIM

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	MixedOff, FOn[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Dwell Time

Table 4-5 Model Summary for the Dwell Time Model for VISSIM

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.859[a]	.738	.738	8.037

a. Predictors: (Constant), MixedOff, FOn

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	521354.4	2	260677.196	4035.474	.000[a]
	Residual	184939.6	2863	64.596		
	Total	706294.0	2865			

a. Predictors: (Constant), MixedOff, FOn

b. Dependent Variable: Dwell Time

Coefficients[a]

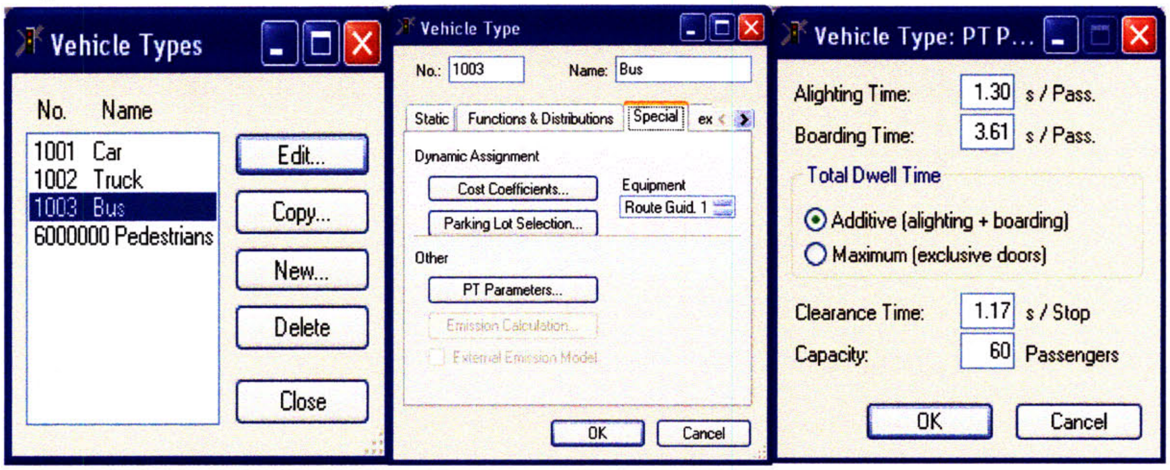
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1.167	.232		5.026	.000
	FOn	3.608	.040	.874	89.630	.000
	MixedOff	1.302	.055	.230	23.538	.000

a. Dependent Variable: Dwell Time

The model estimation results are shown in Table 4-4 and 4-5. Even with only two variables, the explanatory power (the adjusted R square of 0.738) of the dwell time model is satisfactory, compared to Milkovits' previous studies (where his adjusted R squares ranged from 0.72 to 0.74).

The model indicates that each passenger needs an average of 1.30 seconds to alight and 3.61 seconds to board, while the average bus door clearance time is around 1.17 per stop. These parameters can be entered to the VSISSIM model through the Vehicle Type function module as we discussed previously (see Figure 4-29).

Figure 4-29 Dwell Time Input in VISSIM



No.	Name
1001	Car
1002	Truck
1003	Bus
6000000	Pedestrians

No.: 1003 Name: Bus

Equipment: Route Guid. 1

Alighting Time: 1.30 s / Pass.

Boarding Time: 3.61 s / Pass.

Total Dwell Time

● Additive (alighting + boarding)

○ Maximum (exclusive doors)

Clearance Time: 1.17 s / Stop

Capacity: 60 Passengers

Source: the author, 2009

4.5 Model Calibration

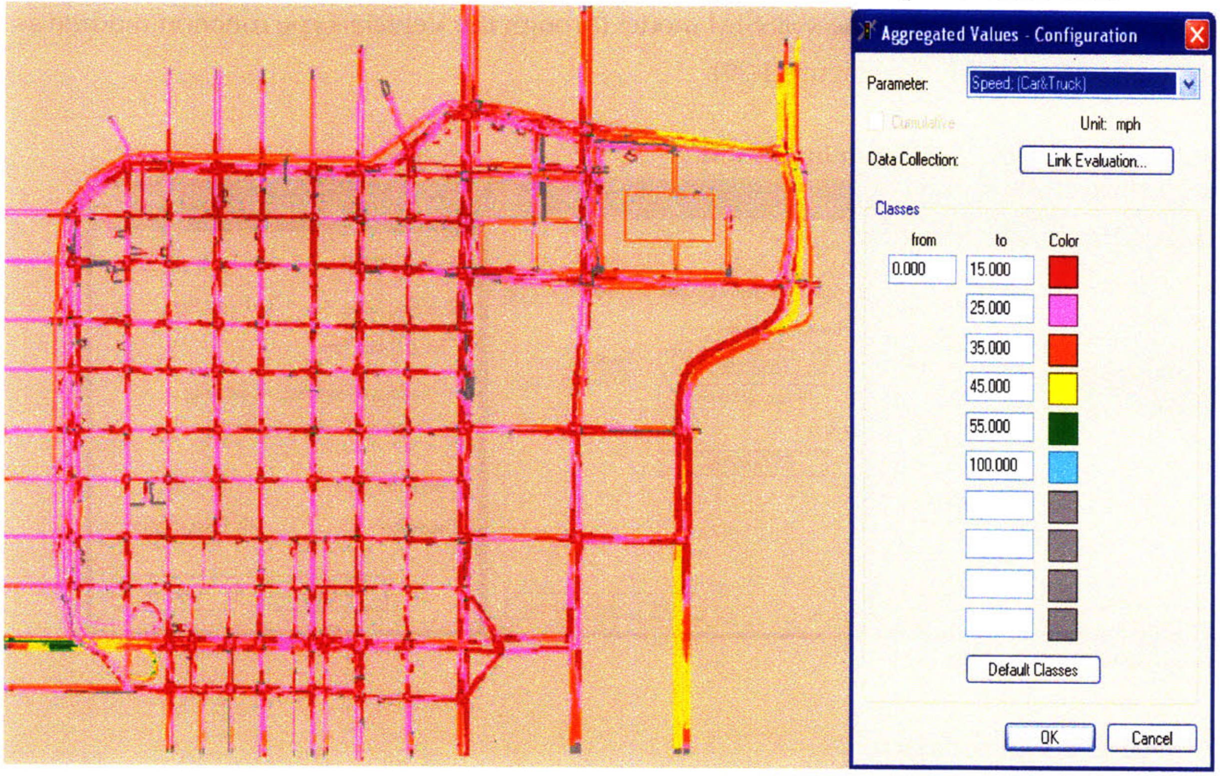
Previous sections have discussed the key elements to prepare the Loop VISSIM Model. Since we have decided to use dynamic traffic assignment method to assign auto traffic, after building the VISSIM model, one important task is to iterate the model and generate a path file which stores the optimal routes for each OD pair by different time periods. An optimal route choice for one OD pair is the minimum time and money cost route chosen from a choice set of K minimum cost routes.

After a high number of model iterations and revisions, the base case model converged. Convergence in the VISSIM model can be defined as a stable status, in which either the variance of travel times or traffic volume on every path compared to its previous run don't exceed a small percentage range, as is customary for most assignment algorithms.

4.5.1 General Traffic: Automobiles

In order to calibrate the Loop VISSIM Model, we need to compare the flows and speeds estimated by this microscopic model with field observations. Given the absence of GPS-based floating car speeds, we opted to calibrate the model by comparing link flows given out extensive availability of field traffic counts. Figure 4-30 shows the average travel speed in PM peak hour (around 17:30) that the Loop VISSIM Model simulated. The color codes represent different travel speed.

Figure 4-30 Aggregated Automobile PM Peak Travel Speed in the Loop VISSIM Model



Parameter: Speed: (Car&Truck)

Unit: mph

Data Collection: Link Evaluation...

Classes

from	to	Color
0.000	15.000	🟥
	25.000	🟪
	35.000	🟧
	45.000	🟨
	55.000	🟩
	100.000	🟦
		⬛
		⬛
		⬛
		⬛

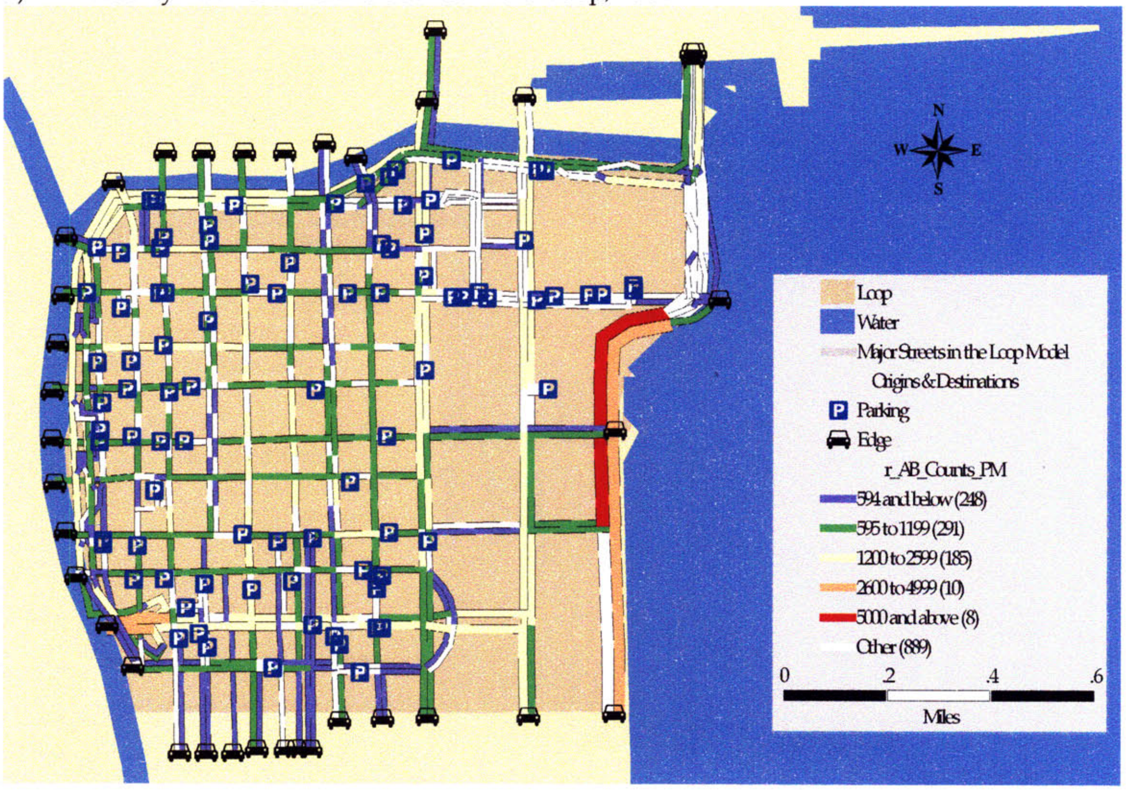
Source: the author, 2009

Link Volume

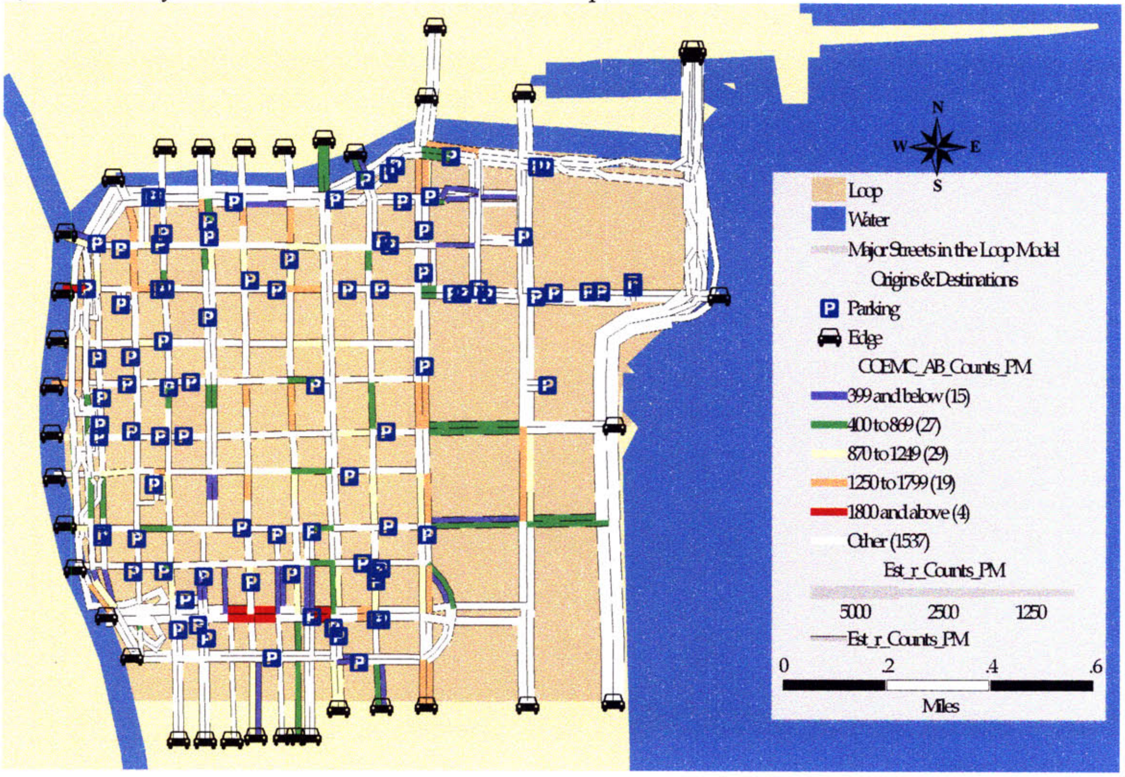
Comparing the observed link volume (PM peak hourly traffic counts in 2004 & 2006) (see Figure 4-31), and estimated link volume by TransCAD and simulated link volume by the VISSIM (see Figure 4-32) we calibrated the VISSIM simulation model. Color codes in these two figures are the same. Figure 4-32 shows that the Link Volume estimated by TransCAD and simulated by VISSIM model are very close to the observed traffic counts in Figure 4-31.

Figure 4-31 Observed PM Peak Hourly Traffic Counts in the Loop, 2004 & 2006

a) Hourly PM Peak Traffic Counts in the Loop, 2004



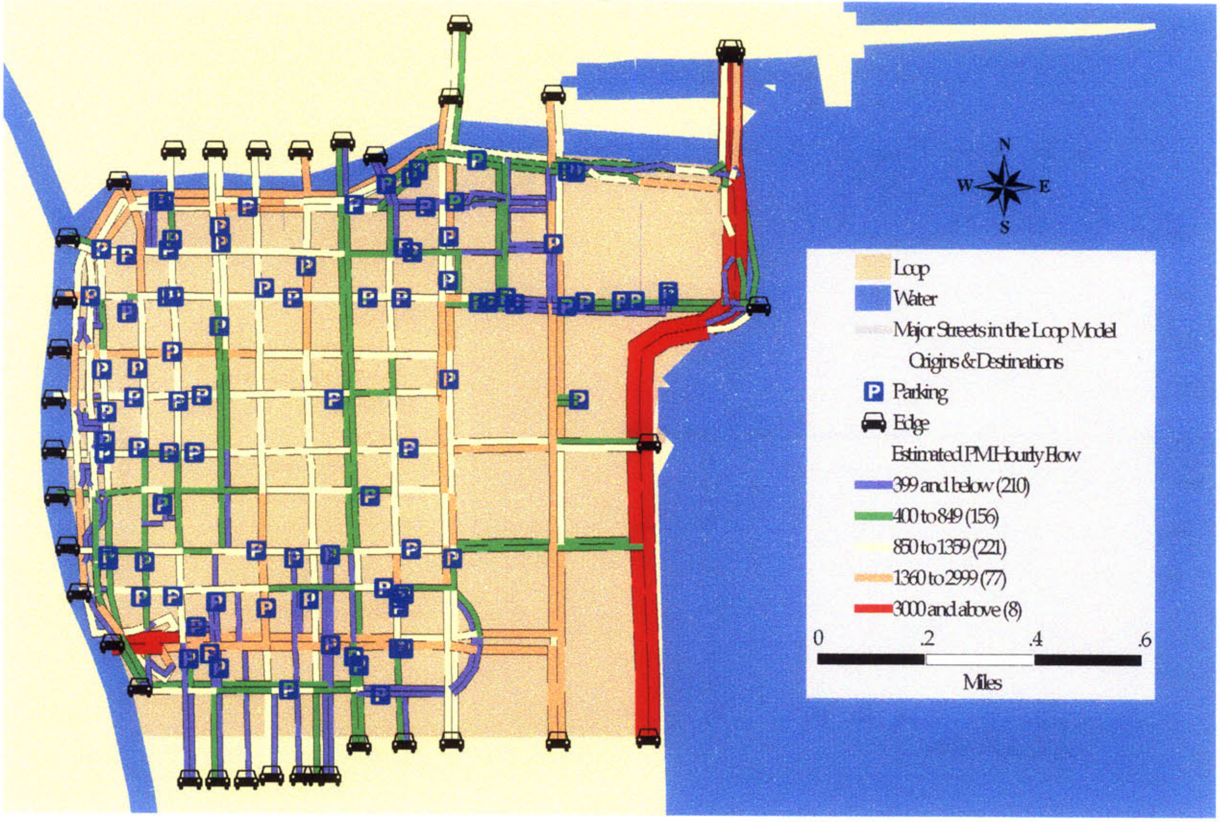
b) Hourly PM Peak Traffic Counts in the Loop, 2006



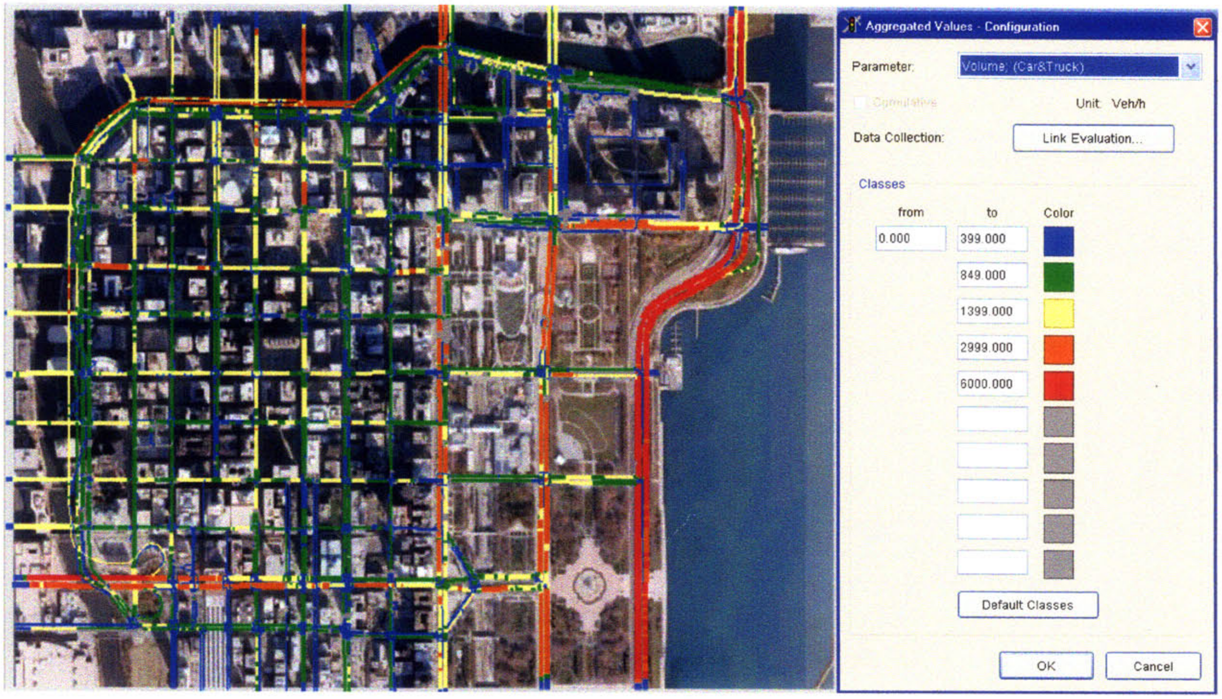
Source: 2004 traffic count data obtained by A. Martin, from the Mayor's Office, City of Chicago, 2004; 2006 traffic count data obtained by the author from OEMC, Chicago, 2006; mapped by the author, 2009.

Figure 4-32 Comparison of Link Volume by TransCAD and by VISSIM

a) Hourly PM Peak Link Volume Estimated by TransCAD



b) Aggregated Hourly PM Peak Link Volume Simulated by VISSIM


Aggregated Values - Configuration

Parameter: Volume; (Car&Truck)

☐ Cumulative

Unit: Veh/h

Data Collection: Link Evaluation...

Classes

from	to	Color
0.000	399.000	🟦
	849.000	🟩
	1399.000	🟨
	2999.000	🟧
	6000.000	🟥
		▨
		▨
		▨
		▨
		▨

Source: the author, 2009

Chapter 5 Definition of Alternative Scenarios & Analytical Results

This chapter describes several potential bus improvement scenarios, and analyzes the impacts of these scenarios on both the automobile and bus performance. In this chapter, we first discuss some key elements that should be considered while defining the scenarios, and later we compare the estimated outcomes of the scenarios to the base case which has been introduced and modeled in the last chapter.

5.1 Rationale of Scenario Building

We cover in this section some key criteria that are helpful in formulating the scenarios strategically.

5.1.1 Bus Lanes to Improve Speed and Reliability

As aforementioned in Chapter 2, the number of CTA bus routes serving the Loop area are 48, compared to 156 for the whole CTA statutory in 2007, although the Chicago Loop represents only 0.16% of the total area of the CTA Statutory.

If we further explore the bus routes concentration in the Loop area, we find that among the 48 CTA bus routes running through the Loop area, 31 of them have stops on Michigan Avenue. That is to say, around 65% of the CTA buses that serve the Loop area run on (at least sections of) Michigan Avenue (see Table 5-1).

Bus lanes not only increase bus speeds, but most importantly, improve the reliability of the bus service by isolating the bus system from the negative impact of road and street congestion. This policy is reinforced by the US DOT funding of CTA to implement a Bus Rapid Transit Program.

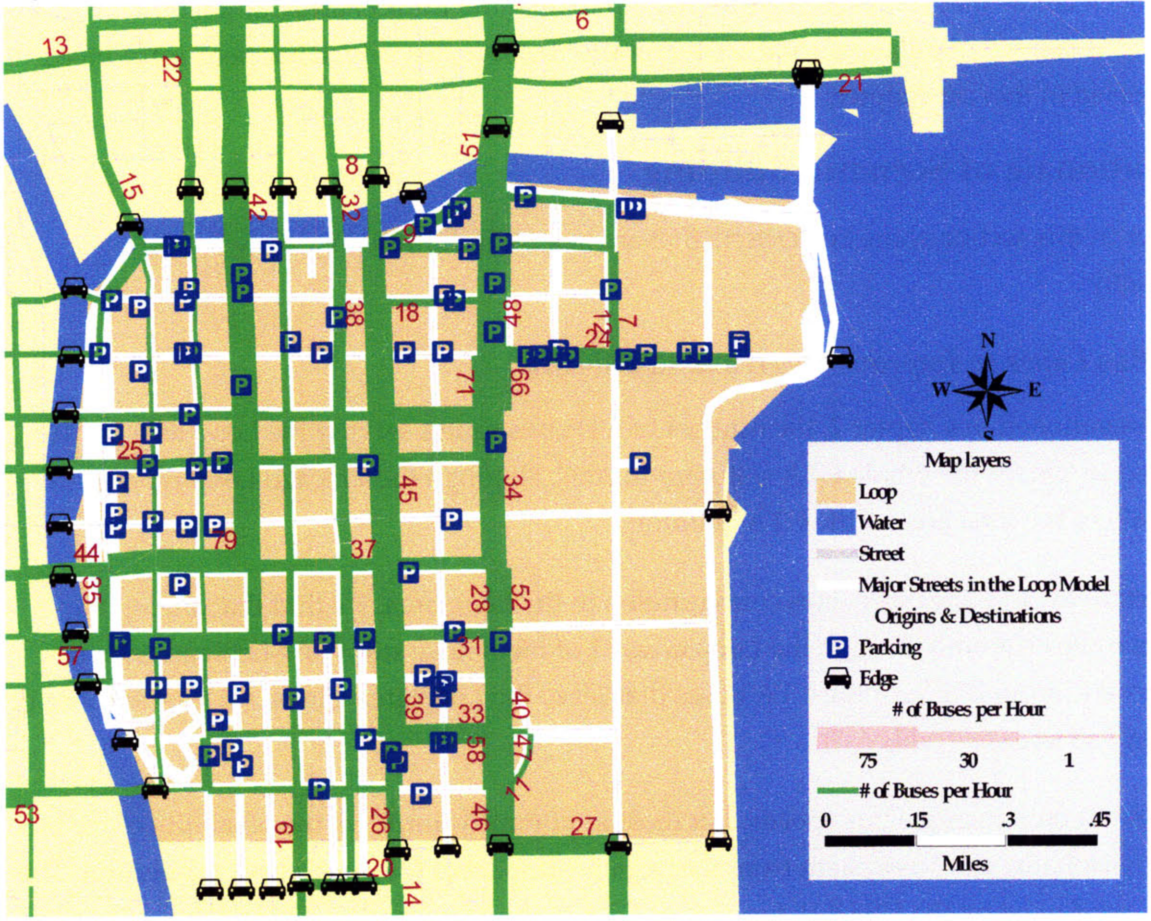
Table 5-1 CTA Bus Routes Concentration Location Comparison

	Michigan Ave	Loop	CBD	CTA Statutory
Area (Square Mile)	n.a.	1.15	3.75	738.69
Percentage	n.a.	0.16%	0.51%	100.00%
Bus Routes	31	48	57	156
Percentage	19.87%	30.77%	36.54%	100.00%
	54.39%	84.21%	100.00%	
	64.58%	100.00%		

Source: calculated by the author from the CTA GIS data, 2007

During peak hours, 34 to 66 buses per hour run on Michigan Avenue; 19 to 45 on State Street; 25 to 40 on both Washington and Madison Streets, and 30 to 57 on both Adams and Jackson Streets (see Figure 5-1). These figures tell that if we have dedicated bus lanes on Michigan Avenue, State Street, Washington and Madison Streets, we will be addressing a social equity issue by redistributing the street space, not just in terms of vehicle occupancy, but in more equitable terms by considering the number of people using the infrastructure.

Figure 5-1 PM Peak Bus Frequency on the Chicago Loop Road Network



Source: TrasCAD data provided by M. Murga, 2008; mapped by the author, 2009

5.1.2 Maximize User Benefits

Another criterion to define potential scenarios is to maximize user benefits. For example, the Chicago Loop composes 0.16% of the total CTA statutory, but it concentrates 3.4% of the total CTA bus passenger boardings on an average weekday, which indicates that the density of CTA bus passenger boardings in the Loop area is 21.32 times of that system-wide average. If we look at sections of Michigan Avenue falling in the Loop area, we find that around 34% of the average weekday passenger boardings in the Loop area are on Michigan Avenue. That is to say, bus improvement on Michigan Avenue, will greatly benefit CTA bus passengers, given the high concentration of service and patronage in this section of the Loop.

Table 5-2 CTA Daily Bus Passenger Boarding Comparison

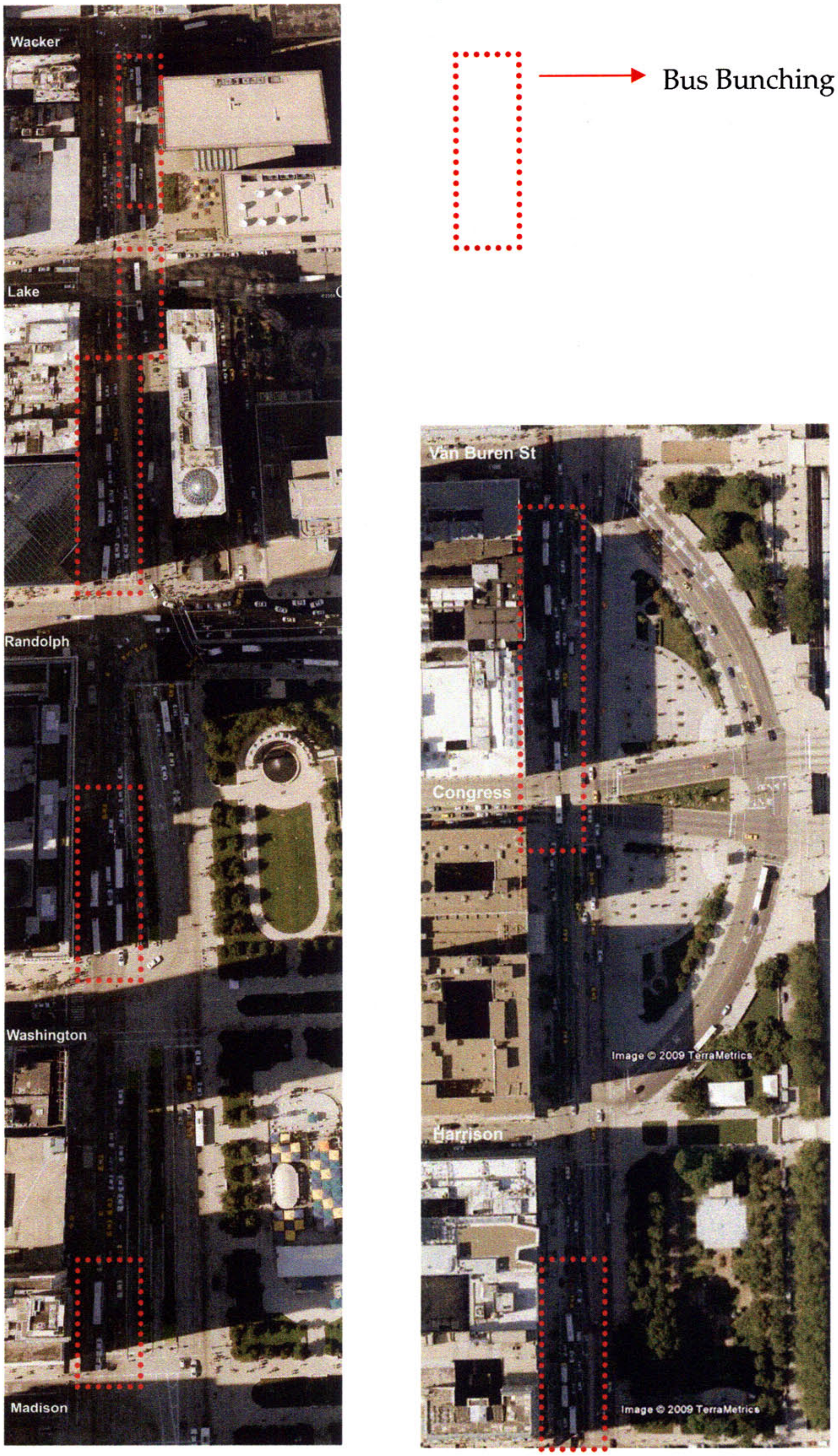
	Michigan Ave	Loop	CBD	CTA Statutory
Area (Square Mile)	n.a.	1.15	3.75	738.69
Percentage	n.a.	0.16%	0.51%	100.00%
Total Daily Bus Boardings	177,050	521,302	1,441,954	15,282,348
Percentage	1.16%	3.41%	9.44%	100.00%
	12.28%	36.15%	100.00%	
	33.96%	100.00%		

Source: calculated by the author from the CTA GIS data, 2007

5.1.3 Reduction of Bus "Pile-Ups" at Stops

While observing the base VISSIM model that has been calibrated as described in Chapter 4, it is apparent that in Michigan Avenue, many buses tend to arrive at the bus stops within a close range of time and/or distance, which makes preceding buses block the succeeding buses. Figure 5-2 show aerial photos of North and South Michigan Avenue, where many buses come after another and as a result bus "pile-ups" can be observed. These aerial pictures were captured on November 5, 2007 and provided by Google Earth. In the vicinity of the intersections of Michigan Avenue with Wacker, Randolph, and Washington, we can clearly see that three or more buses are bunching together around each bus stop. On South Michigan Avenue, similar phenomena can be observed as well.

Figure 5-2 Aerial Photos of Bus Bunching on Michigan Avenue, Chicago, 2007



Source: image of Chicago on November 5, 2007, Google Earth, 2009.

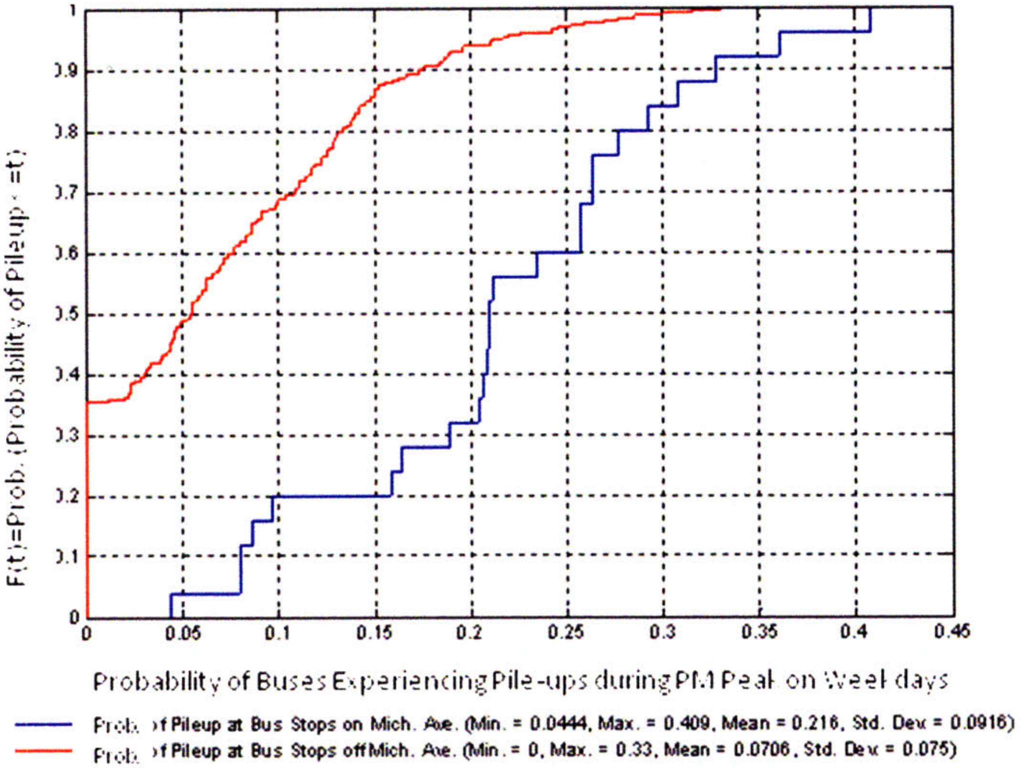
Because the length of the CTA bus stops is usually limited due to the competition of space with other motor vehicles and other sidewalk activities, bus stops cannot accommodate all the arriving buses. Bus "pile-ups" are generated lengthening dwell times of succeeding buses.

We defined a bus has a "pile-up" status, if its arriving time at a bus stop overlaps with the leaving time of a previous bus that stays in the same bus stop. Figure 5-3 shows the empirical cumulative distribution of the probabilities of bus pile-ups at CTA bus stops on/off Michigan Avenue in PM peak hours. The probability is calculated by using the CTA bus history data (for the first week of April, 2007) obtained from the CTA AVAS database according to the formula:

Probability of pile-ups at a bus stop =

\# of bus with pile-ups at the bus stop/ total # of buses dwelled at the bus stop

Figure 5-3 Empirical Cumulative Distribution of the Probability of Bus Pile-ups at CTA Bus Stops On/Off Michigan Avenue in PM Peak Hours

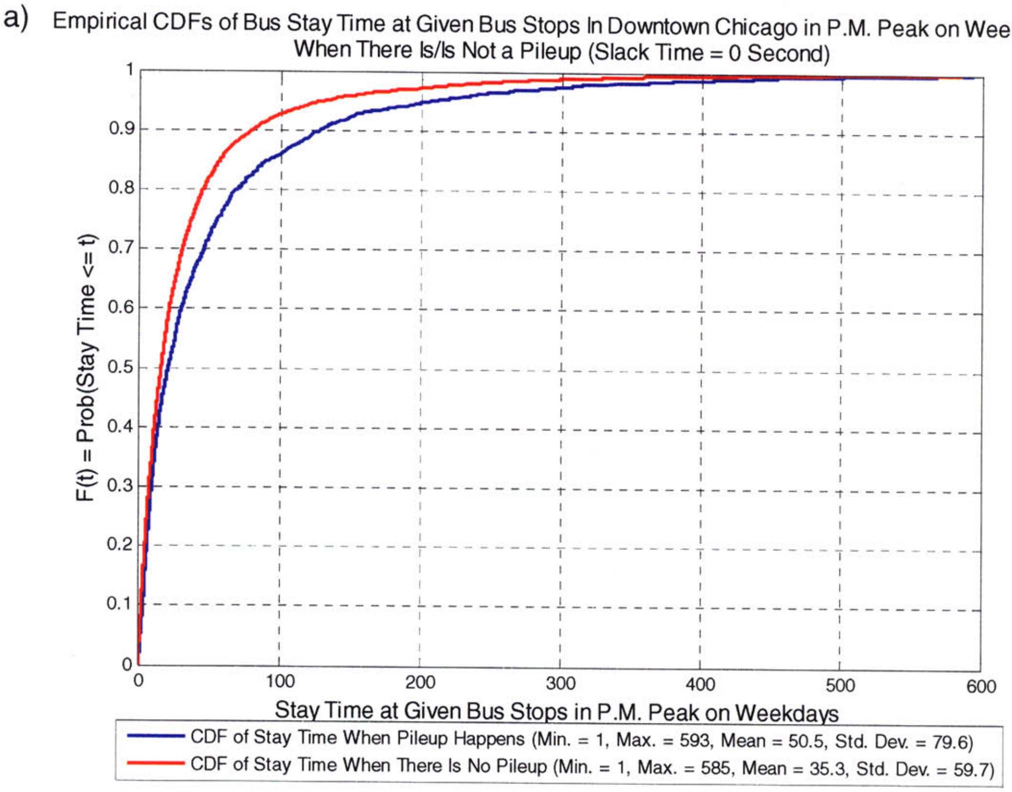


Source: data obtained from the CTA AVAS database, 2008; analyzed by the author, 2008

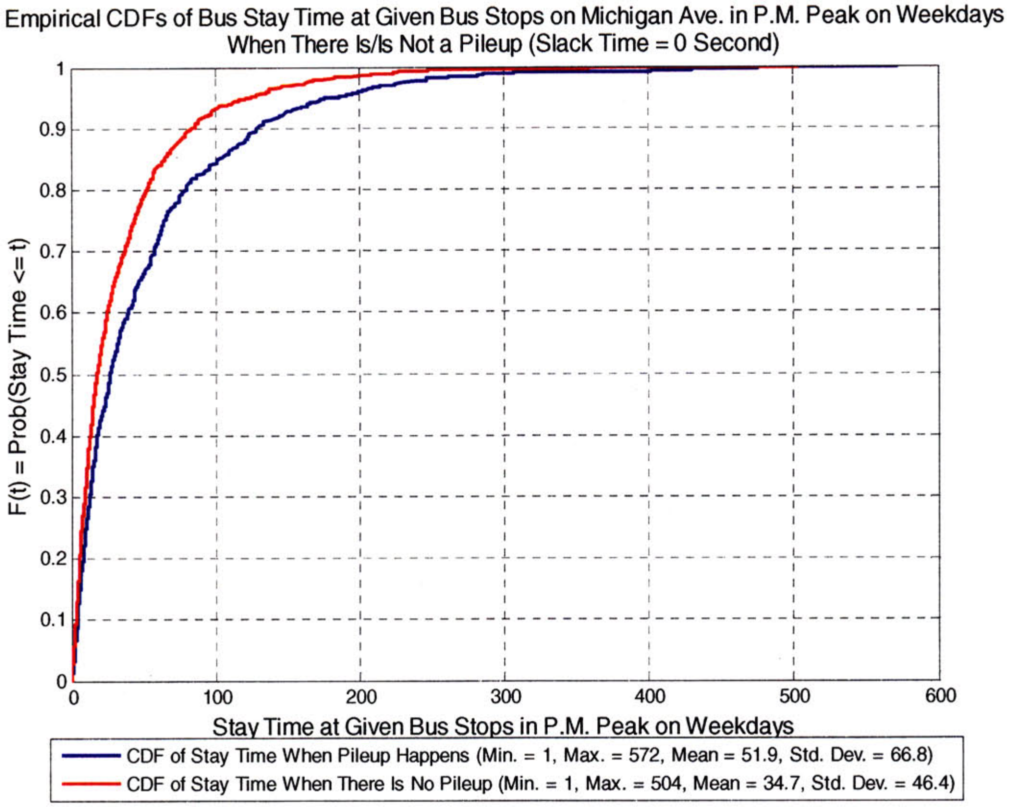
From Figure 5-3, it is clear that the probabilities of pile-ups at bus stops on Michigan Avenue (21.6% on average) are significantly higher than the probabilities at non-Michigan Avenue bus stops (7.06% on average).

We can postulate that higher probabilities of bus pile-ups lead to longer stay-time (time of waiting for buses to enter stops plus dwell time) at bus stops. Figure 5-4.a) validates this conjecture. It presents the empirical cumulative distributions of bus stay-time at all bus stops in the Chicago Loop during PM peak hours. From this figure, we can see that when there is a bus pile-up, the bus stay-time will be 15.2 seconds longer on average than the otherwise average value.

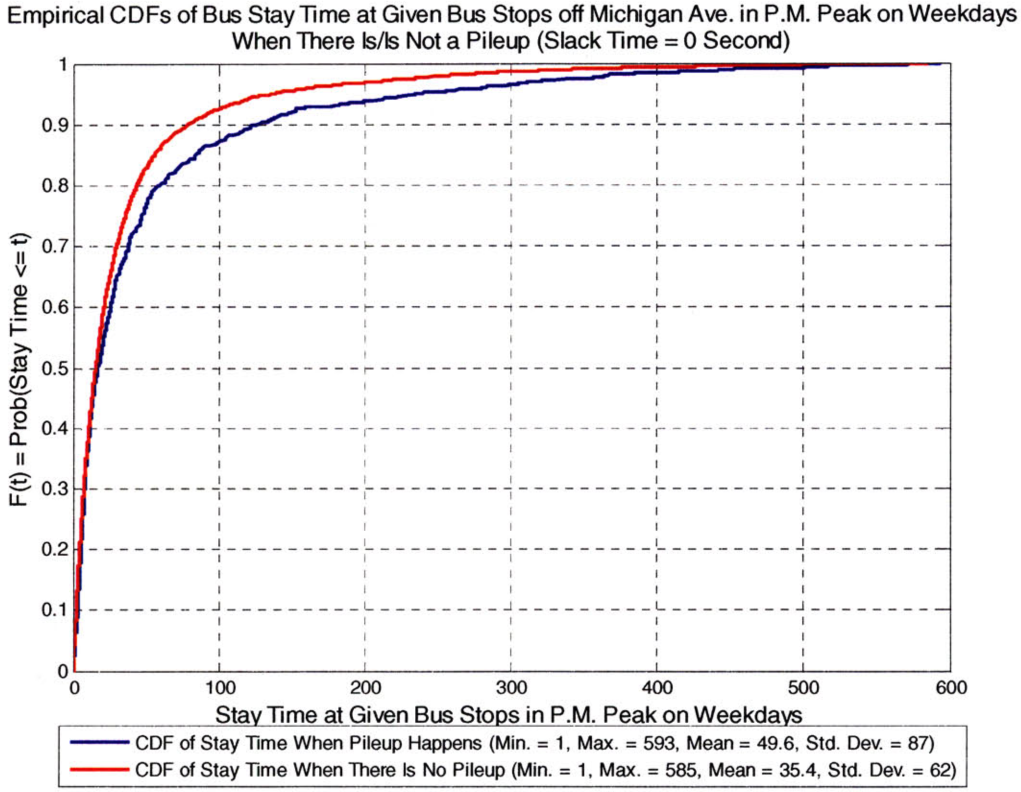
Figure 5-4 Empirical Cumulative Distributions of Bus Stay-Time at Given CTA Bus Stops in the Chicago Loop in PM Peak Hours.



b)


Empirical CDFs of Bus Stay Time at Given Bus Stops on Michigan Ave. in P.M. Peak on Weekdays When There Is/Is Not a Pileup (Slack Time = 0 Second)

c)


Empirical CDFs of Bus Stay Time at Given Bus Stops off Michigan Ave. in P.M. Peak on Weekdays When There Is/Is Not a Pileup (Slack Time = 0 Second)

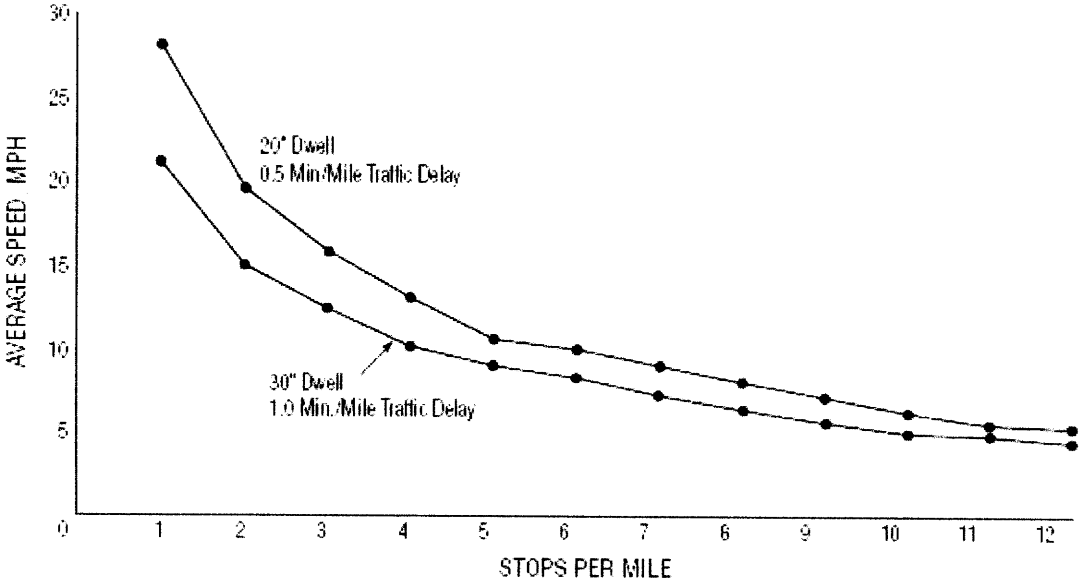
Source: data obtained from the CTA AVAS database, 2008; analyzed by the author, 2008

In order to compare the time-loss due to bus pile-ups both on and off Michigan Avenue, we obtained the empirical cumulative distributions of bus stay-time at bus stops on/off Michigan Avenue during the PM peak hours. The results show that pile-ups cause greater time-loss on Michigan Avenue than on other streets in the Loop area. When a pile-up happens to a succeeding bus, the stay-time (time waiting for entering a stop +dwell time) will be on average 17.2 seconds longer at a bus stop on Michigan Avenue, and 14.2 seconds longer on non-Michigan streets (see Figure 5-4.b and c for the empirical distribution).

There are several potential reasons for this phenomenon. First, bus density/frequency on Michigan Avenue is higher than off Michigan Avenue. Second, passenger boardings on Michigan Avenue is greater than off Michigan Avenue (see Table 5-2, Figure 2-15), which makes the dwell time of potential preceding buses even longer on average compared to those off Michigan Avenue. This will lengthen the waiting time for succeeding buses attempting to enter a bus stop.

Other studies that have studied factors that influence dwell time, for instance, St. Jacques and Levinson studied the relationship among bus speed, stop frequency, and dwell times (see Figure 5-5). They found that for a given stop frequency, the slower the bus traveling speed, the longer the bus dwell time will become; on the other hand, if given the same bus traveling speed, the more stops per mile (or higher stop frequency), will translate to longer bus dwell time.

Figure 5-5 Relationship between Bus Speed, Stop Frequency and Dwell Times



Source: St. Jacques & Levinson, 2000

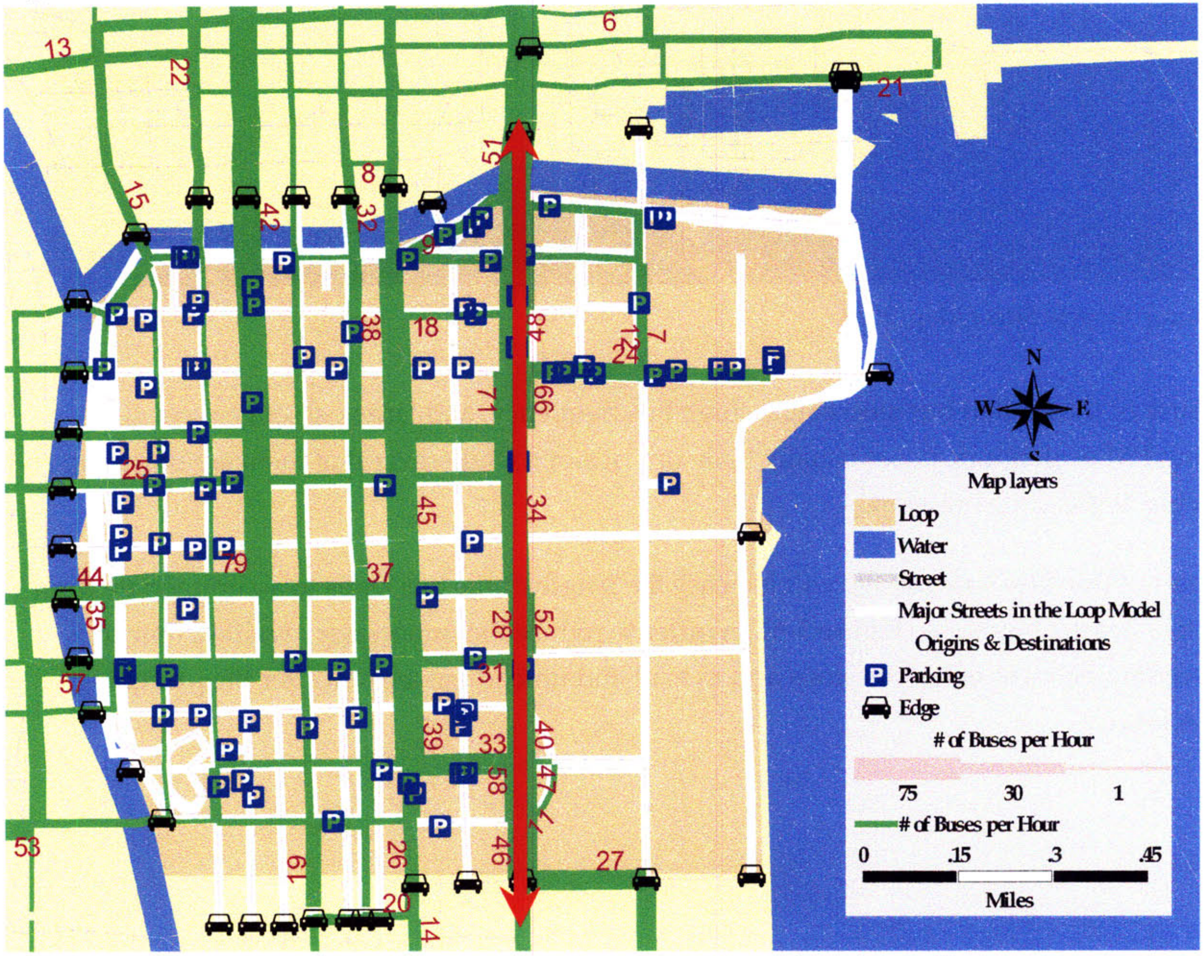
5.2 The Scenarios

Based on the reasoning in the section, and given the existence of bus-only-lanes on Washington Street and Madison Street, two corridors are recommended to run BRT. They are Michigan Avenue, and State Street.

This thesis presents the results for just one of these two potential corridors—Michigan Avenue (see Figure 5-6), just to prove the concept. It will develop three scenarios for bus improvement on the Michigan Avenue corridor to demonstrate its potential contribution.

The three scenarios contain sequential improvements as follows: 1) Increase bus stop length on Michigan Avenue; 2) reconfigure the bus stop pattern on Michigan Avenue; and 3) add a bus-only-lane on Michigan Avenue.

Figure 5-6 Scenario Corridor of BRT in the Loop Area

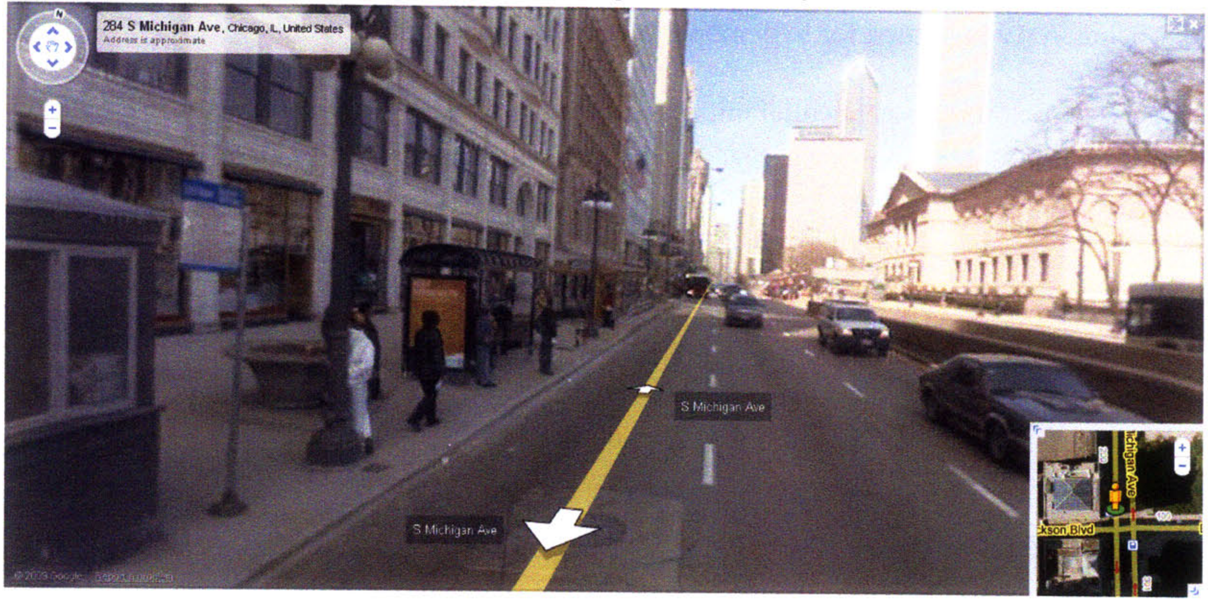


Source: TrasCAD data provided by M. Murga, 2008; mapped by the author, 2009

5.2.1 *Scenario 1: Lengthening Bus Stops on Michigan Avenue*

Urban spaces allocated to bus stops are usually scarce compared to the number of people that use those spaces. This is particular true for the CTA bus stops in the Loop. Figure 5-7 is an image of the CTA bus stop on the south bound Michigan Avenue at Jackson Blvd, which is a standard layout of the CTA bus stops on Michigan Avenue in the Downtown area.

Figure 5-7 A Typical CTA Bus Stop on Michigan Avenue (at Jackson Blvd)

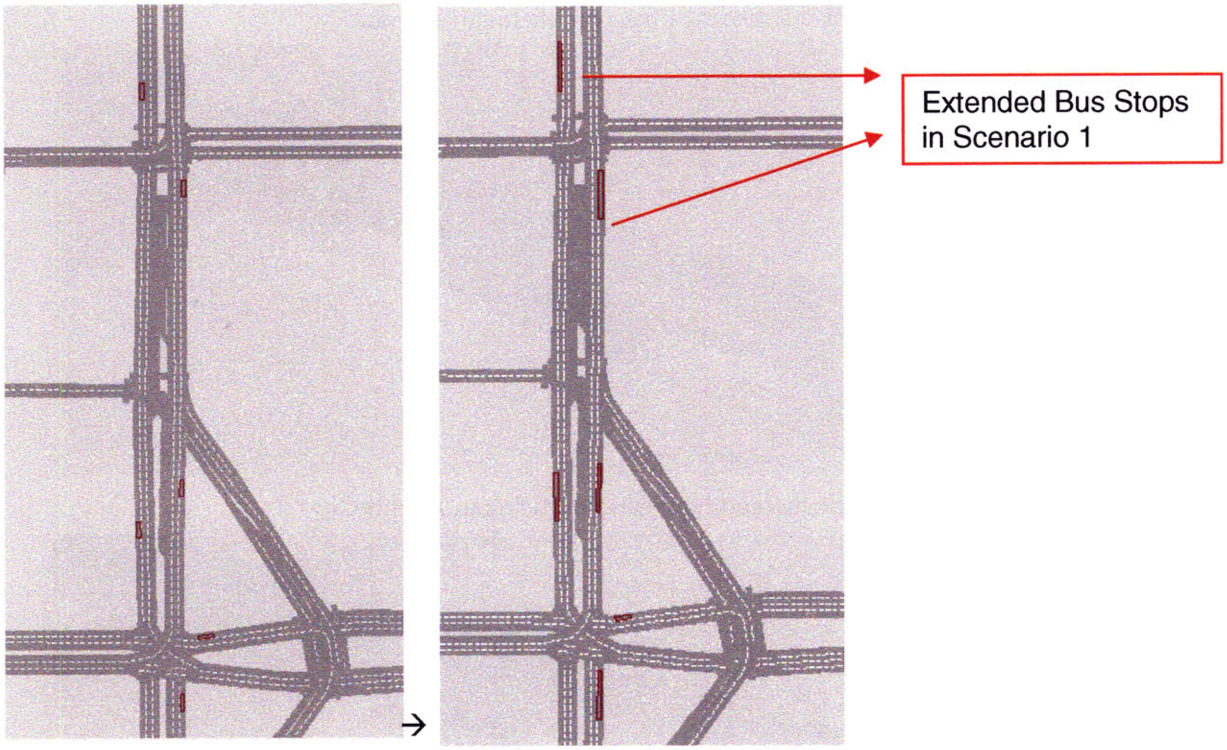


Source: Google Street Map, 2009

Because of the limited bus stop length, high bus frequency, and large passenger boardings during PM peak hours, buses usually "pile up" at stops while several of them are bunching and arriving at the same bus stop.

As part of this first scenario we will increase the length of the bus stops to accommodate from 1 bus to at least 2 buses (see Figure 5-8), in order to reduce the unnecessary waiting time for succeeding buses to enter bus stops and to load and unload passengers after the preceding buses leave.

Figure 5-8 Comparison of Bus Stop Length in Base Case and Scenario 1



Source: the author, 2009

The long bus stops are being proposed in areas prone to clustering to enter bus stops on Michigan Avenue (see Figure 5-2). However, since the bus stops are curbside ones, sometimes cars may occupy the bus stop space while moving, and thus block the succeeding buses which are attempting to enter the stops.

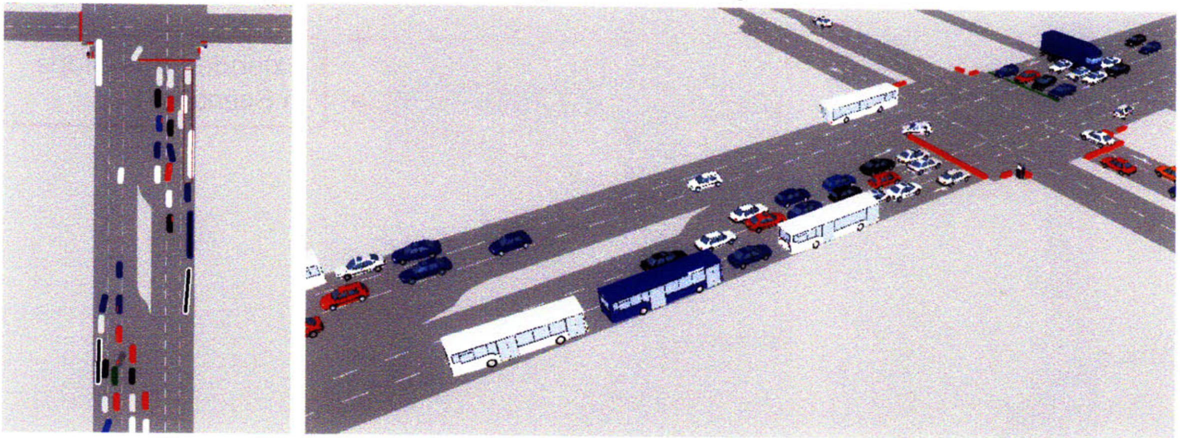
Potential Problems of Scenario 1

Figure 5-9 contains a collection of snapshots at the intersection of Michigan Avenue and Lake Street from the first scenario, simulated by the VISSIM model both in 2-D and 3-D views. They demonstrate cases where bus stops with increased length fail to operate properly.

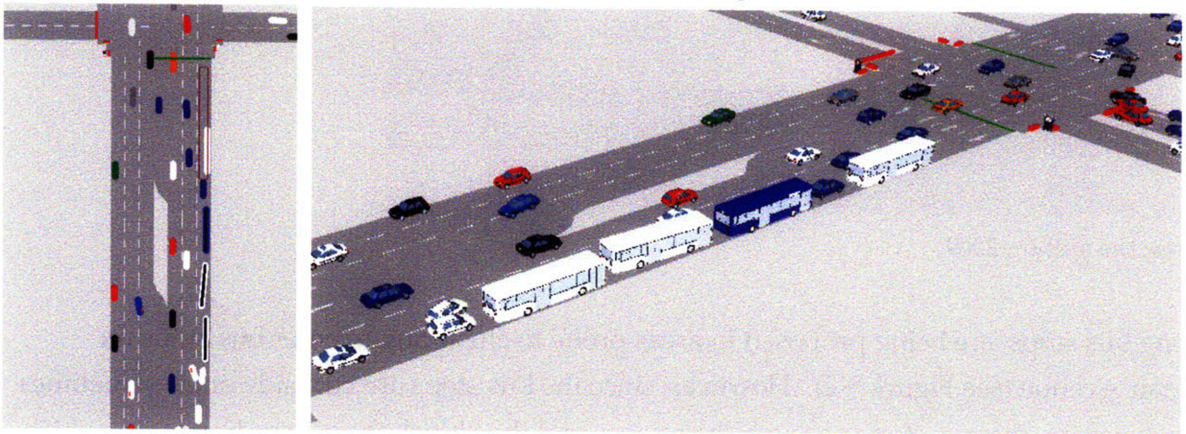
In Figure 5-9, a) reveals the situation in which cars block the near-side bus stop as they are waiting for the signals, and at the same time buses are arriving and trying to enter the stops. In this situation, although the bus stop could accommodate two buses, however, the second bus has to wait till the cars are cleared when the signal turns to green, since half of its space has been occupied by cars.

Figure 5-9 Demonstration of Problems with Scenario 1 Using the VISSIM Model

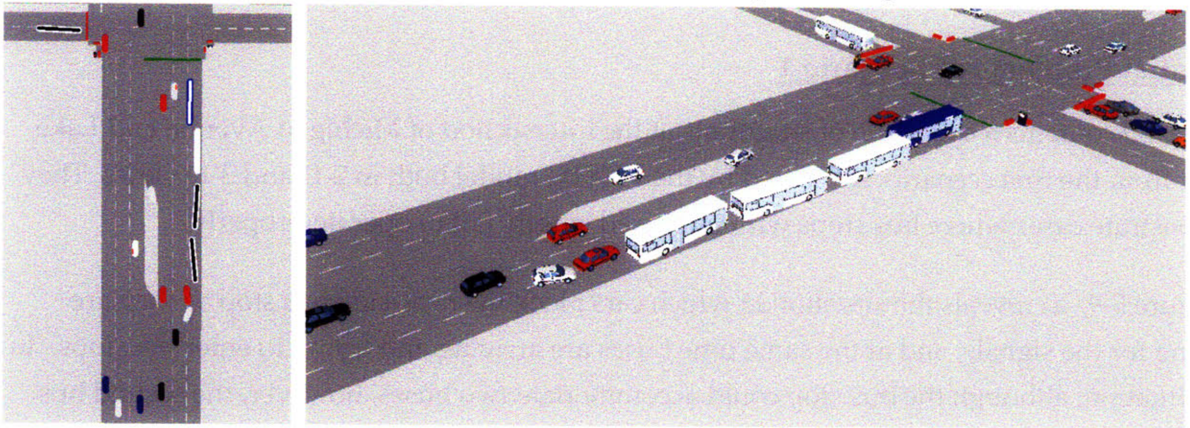
a) Cars occupy bus stop and block succeeding buses on Michigan Avenue.



b) Cars occupy bus stop and block succeeding buses on Michigan Avenue.



c) Preceding buses block succeeding buses at a curbside bus stop on Michigan Avenue.

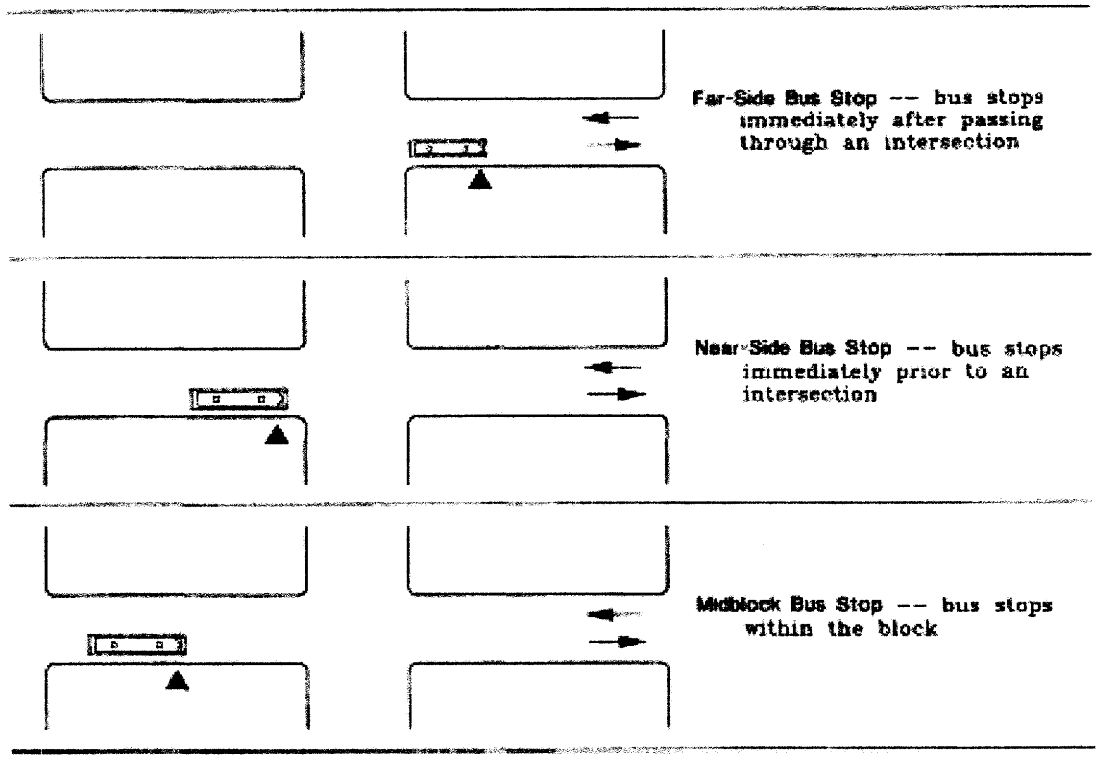


Source: the author, 2009

Figure 5-9.b shows that even when the cars are just in front of the intercections, the second bus cannot enter the stop, since there is another car between it and the first bus. Figure 5-9.c illustrates that the second bus has to wait untill the "sandwich" car drives away, and passes by the first bus to enter the stop to load and unload passengers. Since the bus stop is designed to accommodate two buses, therefore if more buses are clustering to enter the stop, the succeeding ones have to wait unitl the stop clears. Apparently, a large amount of time lost is incurred in such a situation.

This scenario demonstrates when the extended bus stops do and do not work. It also suggests the importance of considering the advantages and disadvantages of the different bus stop locations: far-side, near-side and midblock (see Figure 5-10). Table 5-3 summaries the pros and cons of the different types of bus stops (TCRP Report 90-2, 2003), which will be very useful for refining bus stop locations in the future.

Figure 5-10 Examples of Far-Side, Near-Side, and Midblock Bus Stops



Source: TCRP Report 19, 1996

Table 5-3 Comparison of Bus Stop Locations

Location	Advantages	Disadvantages
Far-side	• Minimizes conflicts between right-turning vehicles and buses • Provides additional right-turn capacity by making curb lane available for traffic • Minimizes sight distance problems on intersection approaches • May encourage pedestrians to cross behind the bus, depending on distance from intersection • Creates shorter deceleration distances for buses, since the intersection can be used to decelerate • Buses can take advantage of gaps in traffic flow created at signalized intersections • Facilitates bus signal priority operation, as buses can pass through intersection before stopping	• May result in intersections being blocked during peak periods by stopped buses • May obscure sight distance for crossing vehicles • May increase sight distance problems for crossing pedestrians • Can cause a bus to stop far-side after stopping for a red light, interfering with both bus operations and all other traffic • May increase the number of rear-end crashes since drivers do not expect buses to stop again after stopping at a red light • Could result in traffic queued into intersection when a bus stops in the travel lane
Near-side	• Minimizes interference when traffic is heavy on the far side of the intersection • Allows passengers to access buses close to crosswalk • Intersection width available for bus to pull away from the curb • Eliminates the potential for double-stopping • Allows passengers to board and alight while stopped for red light • Allows drivers to look for oncoming traffic, including other buses with potential passengers	• Increases conflicts with right-turning vehicles • May result in stopped buses obscuring curbside traffic control devices and crossing pedestrians • May cause sight distance to be obscured for side street vehicles stopped to the right of the bus • Increases sight distance problems for crossing pedestrians • Complicates bus signal priority operation, may reduce effectiveness or require a special queue-jump signal if the stop is located in the parking lane or a right-turn lane
Midblock	• Minimizes sight distance problems for vehicles and pedestrians • May result in passenger waiting areas experiencing less pedestrian congestion	• Requires additional distance for no-parking restrictions • Encourages passengers to cross street mid-block (jaywalking) • Increases walking distance for passengers crossing at intersections

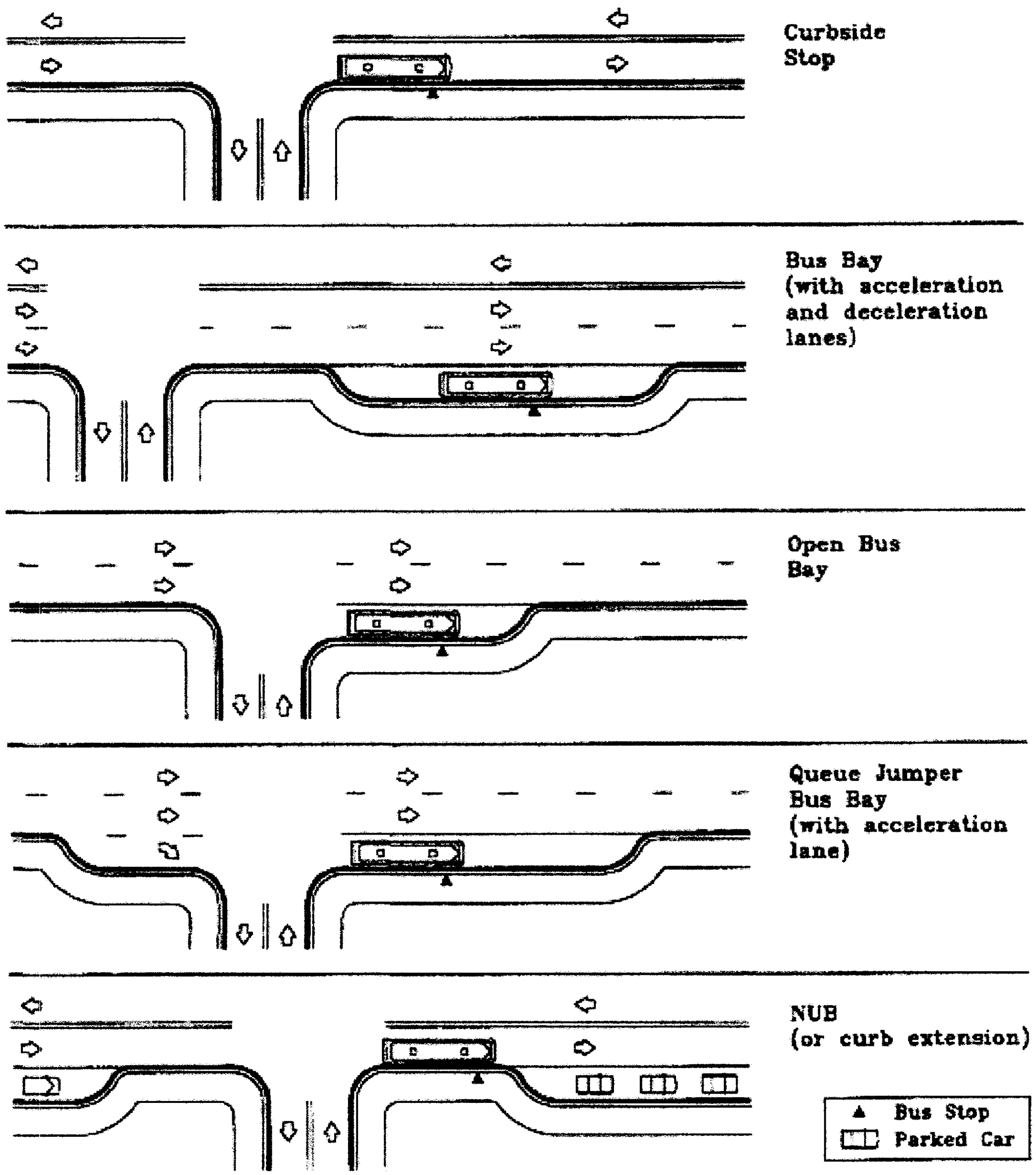
Sources: TCRP Report 90 (2), 2003

5.2.2 *Scenario 2: Changing from Curb-side Bus Stops to Bus Bays*

In the last part of Scenario 1, we discussed some of the potential problems that may occur in curbside bus stops; in this scenario, we will try to address these issues in areas with high frequency service with high demand and presence of high traffic flows.

The Transit Cooperative Research Program (TCRP) Report 19 (1996) summarizes various configurations of street-side bus stops (see Figure 5-11).

Figure 5-11 Street-Side Bus Stop Design



Source: TCRP Report 19, 1996

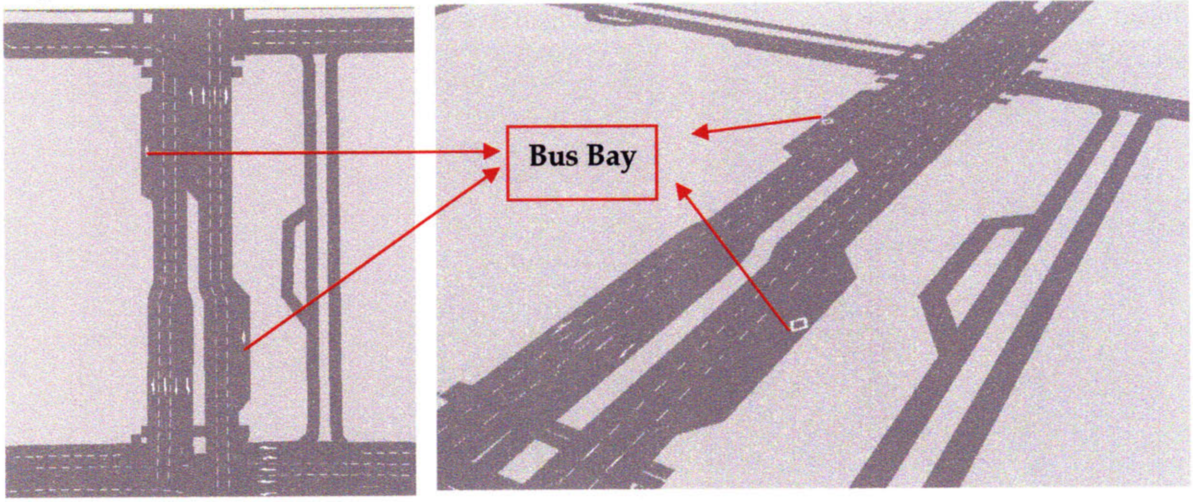
In the same report, it also provides several considerations for the installation of bus bays, among which the followings apply to our study case: 1) bus volumes are 10 or more per peak hour (see Figure 5-6); 2) passenger volumes exceed 20 to 40 boarding per hour (see Table 5-4 that among the 16 bus stops on Michigan Avenue in the Loop, 13 of them meet this requirement); and 3) average peak-period dwell time exceeds 30 second per bus (see Figure 5-4. a)

Table 5-4 Passenger Boardings per Peak Hour at Stops on Michigan Avenue

CROSS_ST	DIR	POS	ROUTESSTPG	BOARDINGS PER HOUR
SOUTH WATER	NB	NS	3,X3,X4,6,19,20,26,N66,143,144,145,146,147,148,151,157	392
RANDOLPH	NB	FS	3,X3,X4,6,19,20,26,N66,143,147,151,173	277
WASHINGTON	SB	NS	3,X3,4,X4,19,20,26,60,N66,124,143,145,147,148,151,157	199
betw. LAKE & RANDOLPH	SB	MB	3,X3,4,X4,19,26,N66,124,143,145,147,148,151,157	198
E. WACKER	NB	NS	3,X3,X4,6,19,20,26,N66,143,144,145,146,147,148,151,157	189
JACKSON	SB	NS	3,X3,4,X4,14,26,127,145,147,148,151	188
betw. MADISON & MONROE	SB	MB	3,X3,4,X4,26,145,147,148,151	164
betw. VAN BUREN & CONGRES	SB	MB	1,3,X3,4,X4,7,14,26,X28,126,127,129,130,132,145,147,148,151	133
SOUTH WATER	SB	NS	3,X3,X4,19,26,N66,143,145,147,148,151,157	123
JACKSON	NB	NS	1,3,X3,4,X4,6,7,14,26,X28,126,127,129,130	55
HARRISON	SB	NS	1,3,X3,4,X4,14,26,X28,127,129,130,151	27
MONROE	NB	NS	3,X3,4,X4,6,14,26,127,173	27
CONGRESS	NB	NS	1,3,X3,4,X4,6,14,26,X28,127,129,130	25
BALBO	SB	NS	1,3,X3,4,X4,127,129	16
MADISON	NB	FT	3,X3,4,X4,6,26,60	13
BALBO	NB	FS	1,3,X3,4,X4,127,129	12

Source: CTA Spring 2007 bus history records; the CTA AVAS database; analyzed by the author, 2009

Figure 5-12 Examples of Bus Bay in Scenario 2



Source: the author, 2009

5.2.3 *Scenario 3: Installing BRT Lanes with Bus Bays on Michigan Avenue*

Even though bus bays alone in Scenario 2 can solve some problems, such as protecting buses from moving vehicles, minimizing delay to through traffic, it still cannot solve the problem of travel delay imposed to buses in mixed traffic. This scenario of bus-only lane with bus bays, as a preliminary version of BRT, tries to address these issues. Scenario 3 is built upon Scenario 2. Here, dedicated bus lanes with bus bays on both sides of Michigan Avenue are modeled in the VISSIM model on top of the extended bus bay scenario.

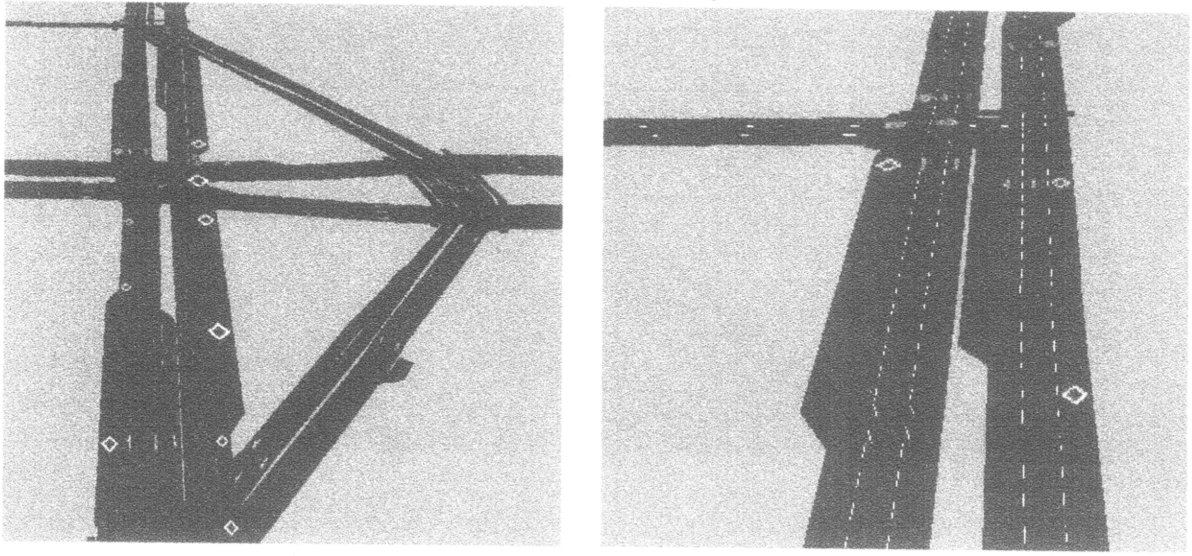
TCRP Report 19 (1996, 24) suggests that the number of bus-loading positions required at a give location depends on 1) the rate of bus arrivals, and 2) passenger service time at the stop. Based on that, bus bays in this scenario are also extended in length in order to accommodate more buses on Michigan Avenue. The installation of a bus-only-lane also allows it to have more space in the bay area.

Figure 5-13 contains some snapshots of the dedicated bus lanes with bus bays on Michigan Avenue in 3D view from the VISSIM model prepared for Scenario 3.

Figure 5-13 Dedicated Bus Lanes with Bus Bays on Michigan Avenue in 3D View

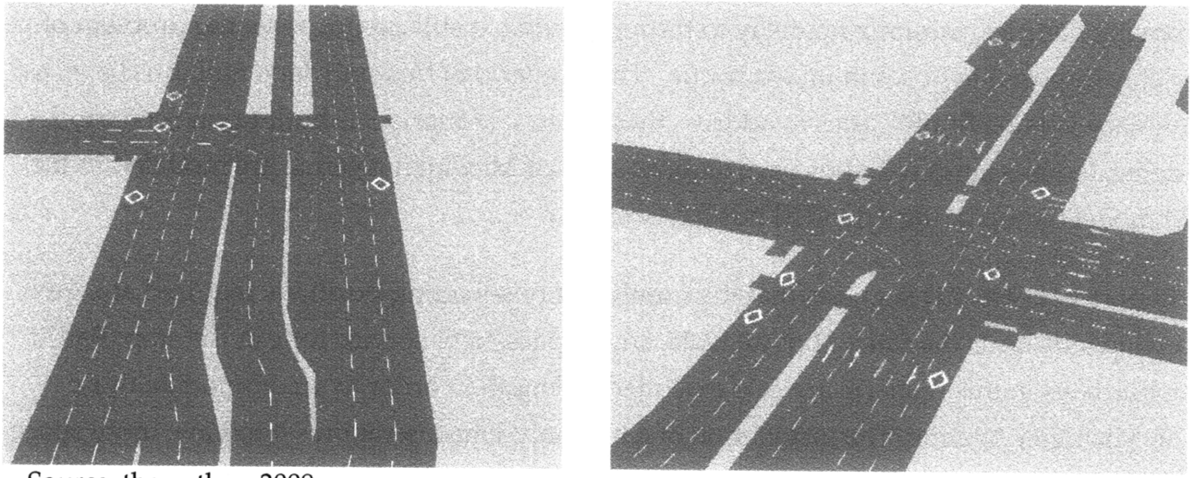
a) Michigan Ave & Congress Pkwy

b) Michigan Ave & Adams St.



c) Michigan Ave & Monroe St.

d) Michigan Ave Randolph St.

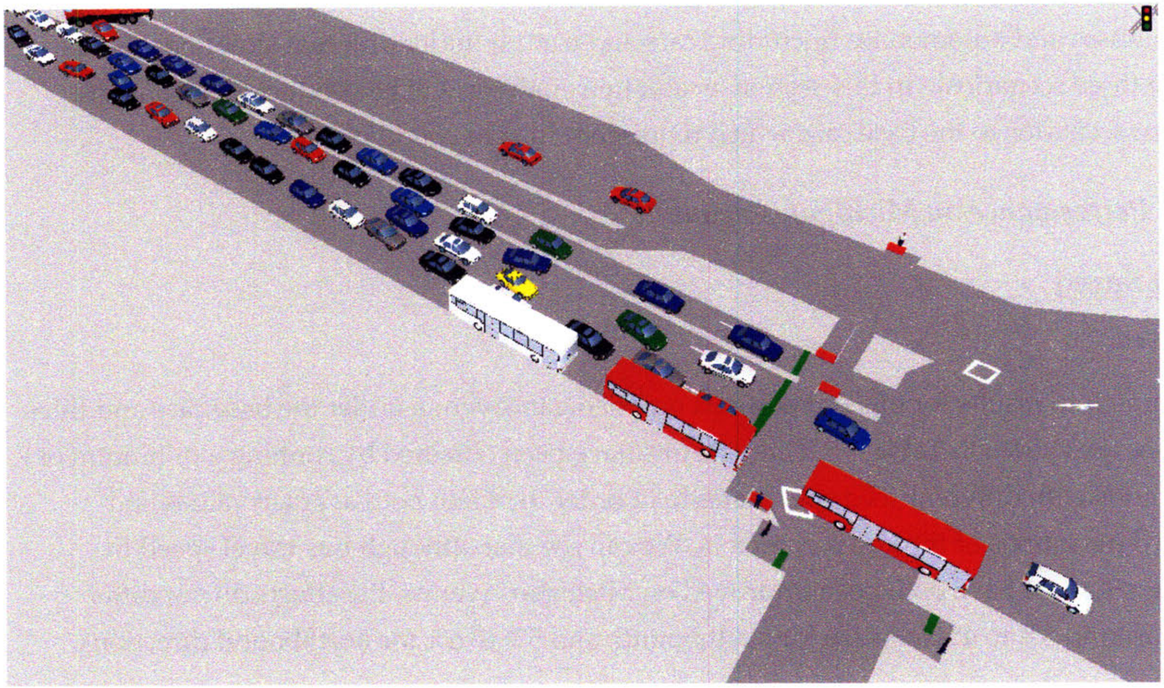


Source: the author, 2009

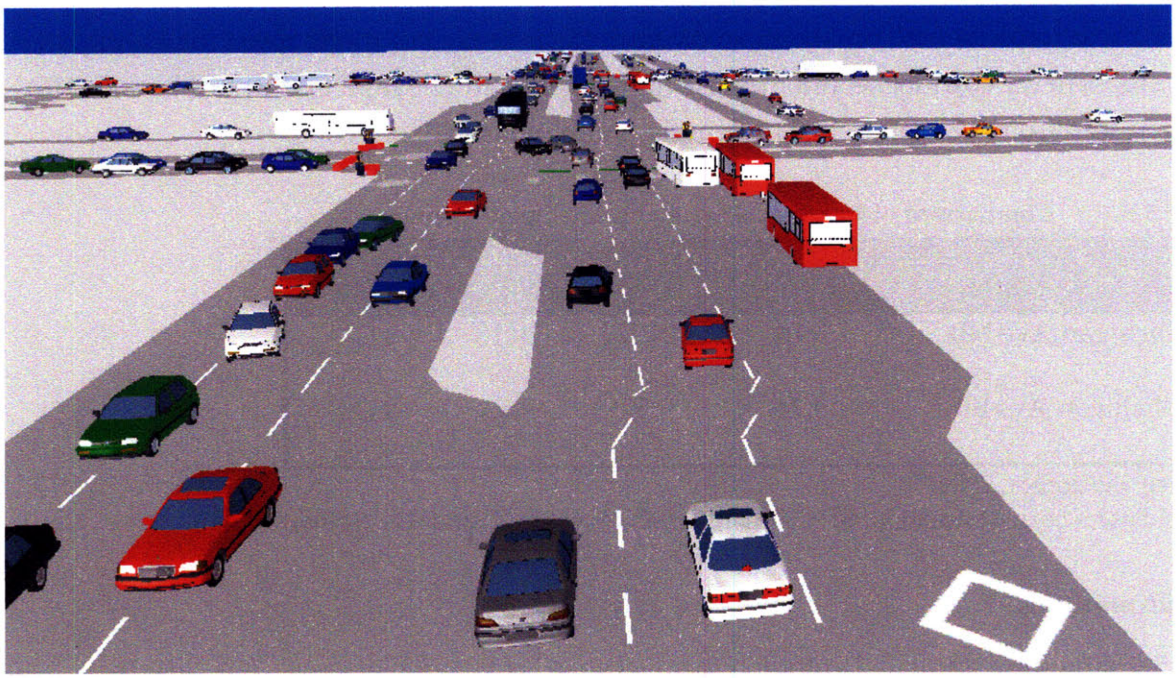
Figure 5-14 include snapshots from the Scenario 3 VISSIM model. It demonstrates that the bus lane has a highly occupancy, due to the high frequency of buses in PM Peak hours on Michigan Avenue. Picture b) illustrates how buses can overtake standing-still buses in the bus bay areas so as to reduce the time-lost induced by waiting for preceding buses to clear from stops.

Figure 5-14 3D Views of Buses Running on BRT Lanes in Scenario 3

a) High bus occupancy of BRT lane on Michigan Avenue



b) Buses can bypass preceding ones near bus bays



Source: the author, 2009

5.3 Evaluation of Scenarios

The VISSIM evaluation function makes it possible to measure the level-of-services for different modes: buses and automobiles (including cars and trucks) under different situations (base case and the three scenarios). In this section, evaluation analyses will be conducted to compare different scenarios to the base case which represents current conditions.

5.3.1 *Performance on Michigan Avenue*

Travel Speed

a). Buses

The simulation results for bus travel speed on Michigan Avenue under the base case and three scenarios are shown in Table 5-5. These results have been obtained by running a minimum of 7 simulations with different seeds per scenario in order to obtain both average values and standard deviations of the key parameters. We can see that although bus travel speed in Scenarios 1 and 2 have both been improved on Michigan Avenue, the effects do not differ much, around 3% to 4% increase for southbound, and 5% to 6% for northbound directions.

However, the scenario with a BRT lane (Scenario 3) shows a strong positive improvement on bus travel speed on Michigan Avenue. Compared to the base case, the average bus travel speeds for both south and north bound directions have increased by 21%. That is to say, if the BRT lane was implemented on Michigan Avenue, the average bus travel speed (including dwell at bus stops) in the corridor would increase from 9.7 mph to 11.8 mph in the northbound (NB) direction, and from 9.2 mph to 11.2 mph in the southbound (SB) direction.

Table 5-5 Comparison of Bus Travel Speed on Michigan Avenue

	Bus Travel Speed (MPH)			
	Base	S1	S2	S3
Michigan Ave NB	9.70	10.27	10.18	11.78
		6%	5%	21%
Michigan Ave SB	9.24	9.59	9.53	11.18
		4%	3%	21%

Source: the author, 2009

Note: Base = current situation, S1 = Scenario 1, S2 = Scenario 2, and S3 = Scenario 3

b). Automobiles

Table 5-6 shows the simulated automobile travel speeds for different cases. It is clear that because of the installation of BRT lane on Michigan Avenue, the capacity for automobiles reduces, and so does the travel speed for automobiles. Compared to the base case, the travel speed for automobiles in the north bound in Scenario 3 decreases by 10% from 12.1 mph to 10.8

mph. For the south bound direction, the auto travel speed reduces by 12%, from 12.9 mph to 11.3 mph. As shown later, this decrease occurs locally, since on the Loop as a whole the impact is particularly small.

Table 5-6 Comparison of Automobile Travel Speed on Michigan Avenue

	Automobile Travel Speed (MPH)			
	Base	S1	S2	S3
Michigan Ave NB	12.11	12.28	12.53	10.84
		1%	4%	-10%
Michigan Ave SB	12.90	13.17	13.37	11.32
		2%	4%	-12%

Source: the author, 2009

Note: Base = current situation, S1 = Scenario 1, S2 = Scenario 2, and S3 = Scenario 3

Since both Scenarios 1 and 2 try to improve bus stop configuration so as to reduce the bus dwell times, street capacity for the automobile is not reduced. Table 5-6 shows that the efforts of improving bus stops have positive impacts on automobile flow. Scenarios 1 and 2 turn to have smoothed the auto traffic and reduced the impact of car traffic on buses. The automobile travel speeds in Scenario 1 increase by 1% to 2% for the two directions of Michigan Avenue, and increase by 4% for both north and south bound directions in Scenario 2.

Apparently, the installation of the BRT lanes on Michigan Avenue (Scenario 3) has shown to be the most effective one in terms of improving bus traveling speed. Although it slows down the automobile traffic by 10% to 12% on average, the absolute speed reduction (1.3mph in north bound direction and 1.6 in south bound direction) is not particularly significant.

Bus Reliability

If comparing bus travel speed does not help to define a better option from Scenario 1 and 2, the comparison of bus travel time reliability serves to identify more reliable services. Table 5-7 summarizes the travel times of buses entering the south end (E. Balbo Ave.) and exiting the north end (E. Wacker Dr.) at Michigan Avenue for the north bound (NB) direction; and vice versa for the south bound (SB) direction. Here, the time interval that has been defined to examine bus average travel time is fifteen minutes, since in the base case it will cost more than 10 minutes (627 seconds for the north bound) for an average bus to run through the north bound Michigan corridor in the VISSIM Loop model. Figures 5-15 and 5-16 are plotted from the data described in Table 5-7.

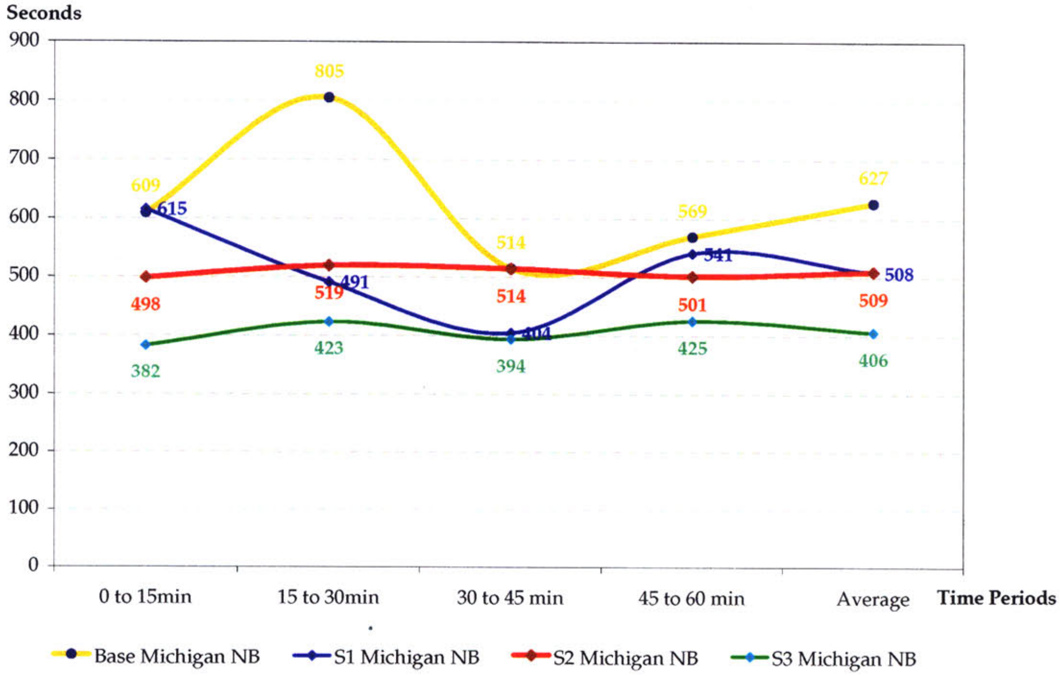
Table 5-7 Comparison of Bus Travel Time on Michigan Avenue

	0 to 15min	15 to 30min	30 to 45 min	45 to 60 min	Hourly Average
Base Michigan NB	609	805	514	569	627
	-2.9%	28.5%	-17.9%	-9.1%	
S1 Michigan NB	615	491	404	541	508
	21.0%	-3.5%	-20.4%	6.3%	
S2 Michigan NB	498	519	514	501	509
	-2.3%	1.8%	0.9%	-1.6%	
S3 Michigan NB	382	423	394	425	406
	-5.9%	4.2%	-3.0%	4.7%	
Base Michigan SB	585	531	532	552	547
	7.0%	-2.9%	-2.8%	1.0%	
S1 Michigan SB	544	537	492	503	519
	4.8%	3.5%	-5.2%	-3.1%	
S2 Michigan SB	472	514	467	513	491
	-4.0%	4.6%	-4.9%	4.3%	
S3 Michigan SB	457	483	442	493	469
	-2.4%	3.0%	-5.6%	5.1%	

Source: the author, 2009

Note: Base = current situation, S1 = Scenario 1, S2 = Scenario 2, and S3 = Scenario 3

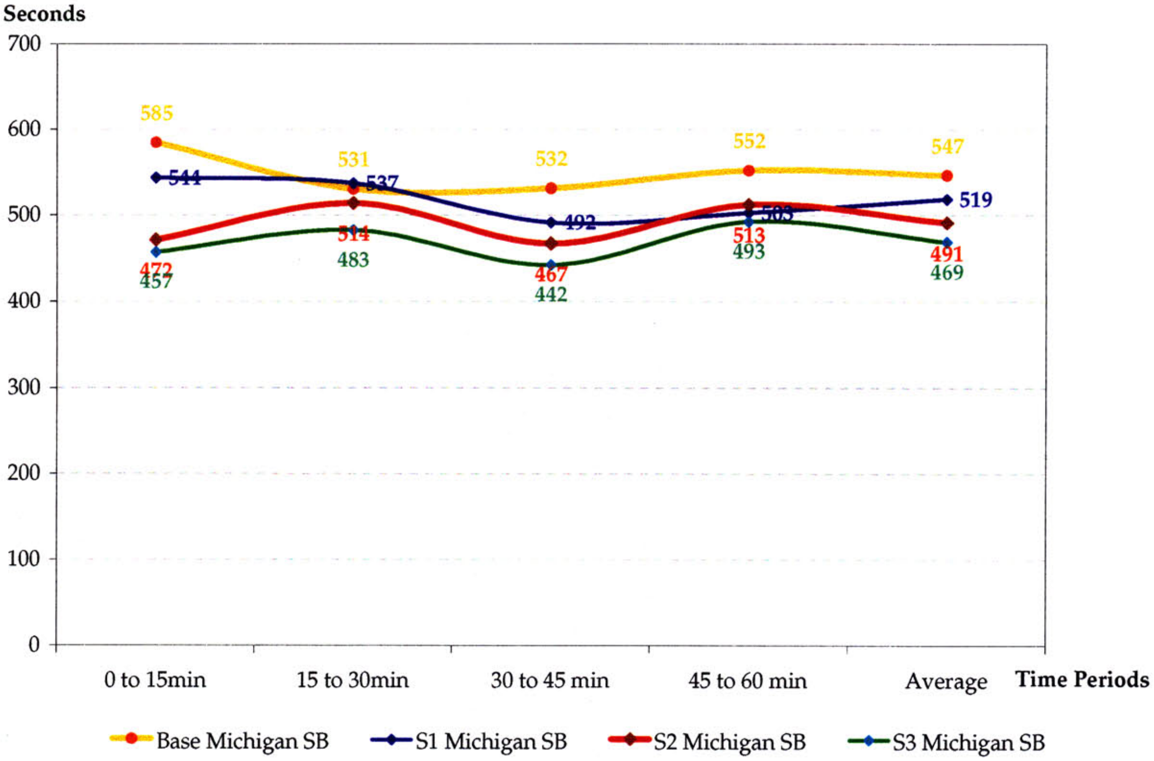
Figure 5-15 Reliability of Bus Travel Time on Michigan Avenue North Bound



Source: the author, 2009

Note: Base = current situation, S1 = Scenario 1, S2 = Scenario 2, and S3 = Scenario 3

Figure 5-16 Reliability of Bus Travel Time on Michigan Avenue South Bound



Source: the author, 2009
Note: Base = current situation, S1 = Scenario 1, S2 = Scenario 2, and S3 = Scenario 3

We can see that for both north and south bound directions, although Scenario 1 has improved bus travel speed (Table 5-5) and thus reduced bus travel time compared to the base case, it does not contribute in improving bus travel time reliability. However, even though buses in Scenario 2 (with bus bays) have slower travel speeds (as discussed previously) and thus longer travel time (103 seconds longer in the north bound, and 22 seconds longer in the south bound) than Scenario 3 (BRT Lane with bus bays), buses in these two scenarios (2 and 3) have similar travel time reliability. This means that Scenario 2 has a positive impact on improving bus reliability compared to Scenario 1 and the base case; and Scenario 3 has contributions in both bus reliability and travel speed improvement, compared to Scenarios 1 and 2, and the base case.

5.3.2 *Performance at the Loop Network Level*

Measuring the impacts of different bus improvement changes on the whole network is also important to evaluate these scenarios.

Travel Speed

a). Buses

The simulation results about bus travel speeds and travel time at the whole loop network level, shown in Table 5-8, tell us that both scenario 1 and scenario 2 have positive effects on bus speeds at the network level. The speed increases range from 1.3% to 3.6% compared to the base case.

Table 5-8 Comparison of Bus Travel Speed and Travel Time in the Network

	Bus			
	Base	S1	S2	S3
Average speed [mph]	7.65	7.75	7.92	7.66
		1.3%	3.6%	0.0%
Total travel time [h]	80.2	80.3	78.9	80.3
		0.1%	-1.5%	0.1%

Source: the author, 2009

Note: Base = current situation, S1 = Scenario 1, S2 = Scenario 2, and S3 = Scenario 3

In terms of total travel time savings, table 5-7 suggests that Scenario 2 saves most (1.3 bus hours) in total during PM peak hour, compared to the base case. If we convert the bus hours into passenger hours to understand the savings for bus passengers, we will see a strong positive impact. Based on the CTA historical data from spring 2007, the average passenger boardings per PM peak hour in the Loop was around 10,524 passengers. By multiplying by a factor of 0.5[1], we estimate that Scenario 2 can save 6840 passenger-hours during a typical PM peak hour in the Loop area.

b). Automobiles

Table 5-9 summarizes the travel speeds and travel time for automobiles under different scenarios at the Loop network level. Comparing the three scenarios with the current base situation, we find that Scenario 2 (installing bus bays on Michigan Avenue) has a positive contribution on reducing congestion for the whole network. The average travel speed for automobiles in the network increases by 4.8% from 11.9 mph to 12.5 mph, compared with the base case. While the BRT lane installation will slightly slow down the auto traffic by 5.5% from 11.9 mph in the current situation, to 11.3 mph.

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[1] Here we assume the average loading factor is 0.5 in order to give an estimation of passenger hour saving.

Table 5-9 Comparison of Automobile Travel Speed and Travel Time in the Network

	Automobiles			
	Base	S1	S2	S3
Average speed [mph]	11.91	11.63	12.49	11.26
		-2.4%	4.8%	-5.5%
Total travel time [h]	3972.0	4068.3	3768.4	4190.6
		2.4%	-5.1%	5.5%

Source: the author, 2009

Note: Base = current situation, S1 = Scenario 1, S2 = Scenario 2, and S3 = Scenario 3

Delay Time

a). Buses

On average, in Scenario 1, the delay time per bus does not seem to change (allowing some error in estimations). However, Scenario 2 shows an average of 8 seconds delay time reduction per vehicle at the network level, which totals to 1.3 to 1.4 hour for all the vehicles that have traveled in the Loop network during the PM peak hour (see Table 5-10). Applying the same concept of passenger-hour delay as explained previously (considering the 10,524 passengers boardings in the Loop area per PM peak hour, and multiplying a loading factor of 0.5), the total delay reduction is around 6800 to 7300 bus passenger-hours in total.

Table 5-10 Comparison of Bus Delay Time in the Network

	Bus			
	Base	S1	S2	S3
Average delay time per vehicle [s]	253	256	245	264
		1.0%	-3.3%	4.2%
Average stopped delay per vehicle [s]	162	163	156	170
		0.7%	-3.3%	5.1%
Total delay time [h]	41.2	41.4	39.8	42.8
		0.7%	-3.3%	4.0%
Total stopped delay [h]	26.2	26.3	25.4	27.5
		0.4%	-3.3%	4.9%

Source: the author, 2009

Note: Base = current situation, S1 = Scenario 1, S2 = Scenario 2, and S3 = Scenario 3

b). Automobiles

Table 5-11 shows the simulated results of delay times in different scenarios. Because of the BRT lane installation on Michigan Avenue in Scenario 3, the capacity for automobiles in that corridor decreases, and the average travel speed reduces as well, from 11.9mph in the base case to 11.3mph in Scenario 3. Many automobiles that used to run through Michigan Avenue will detour, which in turn leads to some delay time for these automobiles. The total delay time for all the automobiles in the Loop network in Scenario 3 increases by 221 hours compared to that in the base case.

Table 5-11 Comparison of Automobile Delay Time in the Network

	Automobiles			
	Base	S1	S2	S3
Average delay time per vehicle [s]	182	190	167	200
		4.4%	-8.3%	10.1%
Average stopped delay per vehicle [s]	104	107	92	111
		3.6%	-11.4%	6.9%
Total delay time [h]	2225.0	2320.9	2029.1	2446.0
		4.3%	-8.8%	9.9%
Total stopped delay [h]	1267.6	1311.2	1117.3	1352.6
		3.4%	-11.9%	6.7%

Source: The Author, 2009

Note: Base = current situation, S1 = Scenario 1, S2 = Scenario 2, and S3 = Scenario 3

Chapter 6 Conclusions and Recommendations

Based on the analyses described in previous chapters, this chapter summarizes 1) the advantages of the methodology—the microsimulation approach— that this study has employed, 2) the policy implications of the different scenarios of bus level-of-service improvement, and 3) potential future research questions and directions.

6.1 Benefits of the Microsimulation Approach for Service Planning

Beyond the advantages that have been discussed in Chapter 4 about the microsimulation approach, based on the scenario testing in Chapter 5, this chapter will emphasize the benefits of the approach for service planning.

6.1.1 *Linking Service Planning with Operations*

Service planning tends to link more closely with operations nowadays than in the past (US DOT FHA, 2004). However, the traditional static modeling cannot contribute as it does not depict the functional and behavioral aspects contained in the microscopic simulation.

The microsimulation approach is behavior based, and can accommodate operations changes in both bus facilities and services (such as frequency, reliability, and fare, etc); thus, it is able to test the feasibility of proposed plans before implementation. The comparison between Scenarios 1 and 2 demonstrates the advantage of microsimulation models well. Even though the two scenarios do not seem to differ much on paper, the simulation results show that Scenario 2(with bus bays) is much more reliable than Scenario 1(extending the length of the curb-side bus stops). If we did not use the microsimulation model to test these two proposals prior to implementation, a potentially ineffective pilot project would have brought this initiative to a halt, risking at the same time the public image of the CTA and the City of Chicago.

6.1.2 *Providing Concrete LOS Estimations*

Without the microsimulation approach, it is impossible to measure the changes of the level-of-service indicators, such as travel speed, reliability, and delay time, for different scenarios. The microscopic simulation approach enables planners and decision-makers to estimate the impact of different bus facility improvements on the general traffic, and the reduction of the adverse effects of automobile traffic on bus services, which other methods cannot predict.

6.1.3 *Facilitating Public Participation*

Microsimulation models can also facilitate public participation in the transportation planning process. They simulate the transportation systems in three dimensions (3-D), which are visually understandable, compared to complicated numbers and analysis that transportation planners often tend to provide. For this reason, using 3-D transportation simulation models to demonstrate the advantages of transit improvement to the public has been recently adopted by a number of transportation agencies, such as the BRT improvement demonstration by the New York City DOT[1]. On the other hand, those 3D visualizations are often critical for the analyst as they may reveal non intuitive interactions among the different modes, as has been the case of Scenarios 1 and 2 in relation to each other.

6.2 Policy Implication of Bus Transit Improvements

6.2.1 BRT Feasibility in Downtown Chicago

Beyond all the important factors that have influenced the proposal contained in Scenario 3—BRT lane on Michigan Avenue, such as the high bus frequency, large volume of passenger boardings and bus bunching (or bus "pile-up") phenomenon along the corridor, the microsimulation also suggests that installing BRT lane on Michigan Avenue is feasible and provides a unique opportunity as a advantageous pilot project, given its predicted performance and its public visibility.

It is worth noting that these analyses have been performed using a constant automobile origin-destination matrix. This is a conservative approach since based on the improvements discussed here; it is plausible that some drivers may end up switching to the bus system, thus contributing to ease some traffic congestion.

The simulation results of Scenario 3 show that the installation of BRT lane on Michigan Avenue will significantly improve the bus travel speed and reliability. Compared to the base case, the bus speed has increased by 21% for both directions,—from 9.7 mph to 11.8 mph in the north bound, and from 9.2 mph to 11.2 mph in the south bound. Its travel time reliability has improved from -9.1% to +28.5% fluctuation from the mean, to -5.9% to +5.1% fluctuation under Scenario 3. It is important to know that these reliability improvements are perceived by transit users as more attractive than simple travel savings, considering that exceeding the trip budgeted time results in higher inconvenience.

Meanwhile, the BRT lane installation will not bring a significant negative impact on automobiles in the whole Loop network —as it will only reduce the automobile travel speed by 5.5% on average, from 11.9 mph in the base case to 11.3mph with BRT lane on Michigan Avenue.

The results suggest that the installation of BRT lane on Michigan Avenue in the Loop area will be feasible, and that it can play an important role as a pilot BRT in Downtown Chicago. After

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[1] Retrieved April 20, 2009 from http://www.nyc.gov.html/dot/.ferrybus/selectbusservice.shtml

the successful implementation of BRT on Michigan Avenue, other corridors in the downtown area can be tested and implemented.

It is recommended that for this pilot project, a simple traffic signal green-wave coordination scheme along Michigan Avenue is implemented, by modifying the off-sets of all Michigan Avenue traffic signals. The two reasons for this low-cost measure are: a) it can be easily implemented and it will reinforce the benefits accrued by the bus-lane, by choosing as the propagation speed, the one corresponding to the average speed of buses; and b) it sends a strong message of support in favor of buses and it strengthens their image as a reliable and effective transport mode.

6.2.2 *Bus Stop Configurations*

Comparing the different simulation results of Scenarios 1(extending curb-side stop length) and 2(installing bus bays), we found that although bus travel speed improvement of both scenarios does not differ much, Scenario 2 has an evident advantage on bus reliability over Scenario 1. In Scenario 2, the fluctuation of travel time from the mean ranges from -4.9% to +4.0%, while in Scenario 1, it ranges from -20.4% to +21%.

This suggests that the design of bus stops does have a significant impact on bus performance. Although simple curb-side bus stops have low cost and easy installation, it can cause traffic queuing and congestion behind stopped buses (TCRP, 1996), or even block buses from entering the stop if cars are occupying the stops. Even extending the length of the curb-side bus stops will not help, and may make the traffic worse when bus density is high, such as the cases on Michigan Avenue during PM Peak hours. For further comparison of different bus stop designs please see Table 6-1 (TCRP, 1996).

Table 6-1 Comparison of Bus Stop Designs

	Advantages	Disadvantages
Curb-side	• Provide easy access for buses • Simple in design and easy and inexpensive to install • Easy to relocate	• Can cause traffic queuing/congestion behind stopped buses • May cause unsafe maneuvers for lane-changing vehicles to avoid a stopped bus
Bus Bay	• Allows passengers to board and alight out of travel lane • Provides buses a protected area away from moving vehicles • Minimizes delay to through traffic	• May introduce problems when buses are re-enter traffic • Expensive to install compared to curbside stops • Difficult and expensive to relocate

Source: adapted from TCRP Report 19, 1996

6.3 Future Research and Applications

This thesis has studied the impacts of several bus facility improvements on bus level-of-service changes. Among three of the studied scenarios, two of them have tested elements of BRT—the BRT bus running way and the stop configuration. In the future, the VISSIM model developed in this thesis can be used to test more BRT corridors and additional elements, such as signal preemption and off-board fare collection.

6.3.1 Additional BRT Corridors

In the future, more corridors in the Loop area, for example, the State Street corridor, can be tested for additional BRT lanes in the VISSIM model. Statistical testing[1] has shown that buses running on State Street tend to have longer dwelling times (2.7 seconds on average) than those running off State Street (not including those on Michigan Avenue). Chapter 5 has explored some of the potential reasons. For example, on State Street, bus frequency during PM peak hours is high—on different sections of the corridor, bus frequency ranges from 19 to 45 buses per hour. Adding BRT lanes on State Street will presumably gain more travel time savings for bus passengers compared to other corridors (not including the Michigan Avenue corridor). The VISSIM microsimulation model developed in this thesis will provide a foundation for testing new BRT lanes and their feasibility by comparing the LOS indicators that have been proposed.

6.3.2 Traffic Signal Priority Enhancement

Traffic signal preemption is another element of BRT that can be tested in the VISSIM microsimulation model in the future. By optimizing traffic signals and providing buses with signal priority along the BRT corridor, planners are able to estimate the travel time and reliability improvements of buses, and the impact of these changes on the general traffic.

6.3.3 Off-Board Fare Collection

This research has not tested the possible improvements on bus dwelling time caused by off-board fare collection, which is another important element of BRT systems. Off-board fare collection as described in Chapter 3 allows passengers to buy and validate tickets before boarding, thus saving passenger boarding times. By changing the dwell time parameters, estimated from new dwell time models based on field data of BRT systems with off-board fare collection mechanisms, the VISSIM models can also simulate and estimate the dwell time savings of buses in different scenarios.

To provide a rough estimate of the potential benefits of this measure, one can consult our fitted dwell-time model (see Table 4-5). The model's boarding coefficient is 3.6 seconds per passenger,

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[1] See Appendix C, Model 2 for more details.

while the alighting coefficient is just 1.3 seconds per passenger. So under off-board fare collection, with entry through any of the bus doors, one can assume savings of 2 seconds per passenger boarding, leading to a total saving of 98.36 passenger-hours per day[1]. The bus dwell time savings also contribute to the reduction of total travel time of bus passengers who ride buses running through the Michigan Avenue corridor. This figure in passenger-hours can be converted to equivalent daily dollar savings by using $4/hour as a minimum monetary value of time savings.

6.3.4 Parking Price Management Strategy

The VISSIM model can also estimate automobile traffic assignment changes under various parking price schema. Most probably, parking cost changes will influence the origin and destination choices of automobile drivers, and thus change the Origin-Destination (OD) input table.

The dynamic assignment method in the VISSIM microsimulation model will calculate the new optimized time and money costs while searching equilibrium routes for automobiles. As the traffic volume of different routes changes, its impacts on the bus performance will change as well. The VISSIM model can simulate the impacts of parking price changes on the traffic assignment change, and on bus LOS performance change.

Figure 6-1 demonstrates this idea. For example, in order to facilitate BRT along Michigan Avenue and State Street, a new scenario has been sketched where the parking prices in the red area (an area between Michigan Avenue and State Street in the studied Loop area) increase significantly. As a result, the propensity of drivers to park in this red area decreases. The VISSIM model can use the new OD matrix as an input, and simulate new bus and automobile performance indicators (such as travel speed, reliability and delay time) under this scenario.

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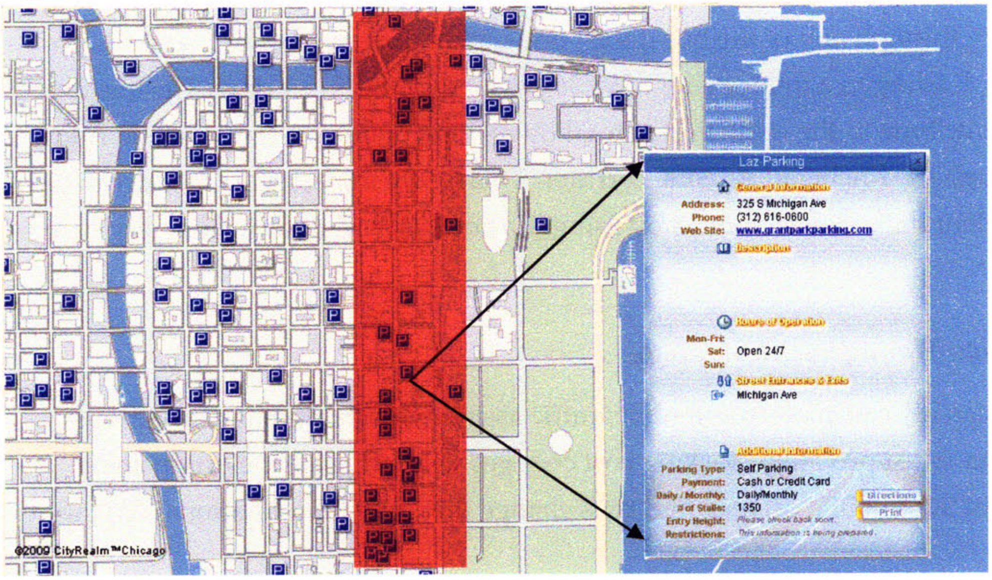
[1] The number is calculated by 2 seconds divided by 3,600 seconds/hour, and multiplied by the total number of daily passengers boardings along Michigan Avenue, 177,050 (see Table 5-2). That is 2/3600*177050=98.36 (hours).

Figure 6-1 Potential Parking Management Schema



Address: 325 S Michigan Ave
Phone: (312) 616-0600
Web Site: www.grantparkparking.com
Mon-Fri:
Sat: Open 24/7
Sun:
Michigan Ave
Parking Type: Self Parking
Payment: Cash or Credit Card
Daily / Monthly: Daily/Monthly
# of Stalls: 1350
Entry Height: Please check back soon.
Restrictions: This information is being prepared.

Source: the Parking Industry Labor Management Council, 2008. Retrieved January 20, 2009, from http://www.chicagoparkingmap.com/map_static.jsp

6.3.5 Congestion Pricing Extension

As an extension of parking management, a road congestion pricing mechanism may also be included as a future scenario. ITS devices could be installed under this scenario, in which automobiles entering the predefined areas (such as the red rectangle demonstrated in Figure 6-1) would be automatically charged a road congestion fee. The road congestion charge can be allocated to transit agencies to purchase new bus vehicles in order to enhance the BRT services. The VISSIM model can be tuned to test the total congestion charging, and the traffic volume changes, and its impact on bus performance improvement.

6.3.6 Energy Consumption and GHG Emissions

The simulation model can also estimate Green House Gas emission changes, and energy (e.g. fossil fuel) consumption changes under different scenarios. These aspects are crucial for sustainable development of the study area. Based on the vehicle type input (both for automobiles and buses), the VISSIM model[1] can estimate the different emission components (such as CO, CO_2, NO_x, SO_2), and fuel consumption.

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[1] PTV-AG Emission add-ons are needed to realize this function (PTV, 2007).

6.4 Thesis Conclusion

Chicago has experienced a great many challenges brought by traffic congestion, which limits regional mobility, induces a huge amount of energy waste and Greenhouse Gas emissions, impedes economic development, and decreases bus reliability and travel speed. Bus rapid transit (BRT) turns to be a promising alternative to reduce negative impacts of traffic congestion. However, how to evaluate the impacts of such policies on different stakeholders (i.e., auto-drivers and bus-riders) prior to its implementation is vital for planners and policy-makers to make sound decisions.

This thesis approaches the above question relying on the preparation of a VISSIM microscopic traffic simulation model for the Chicago Loop area. It proposes three sets of indicators for the purpose of evaluation of the proposed schemes: 1) bus and auto travel speed, 2) bus reliability, and 3) bus and auto delay time. These performance indicators serve to compare the current base case and three proposed bus improvement scenarios: 1) extending curb-side bus stop length, 2) changing the curb-side bus stops to bus bays, and 3) adding BRT lanes with bus bays on the Michigan Avenue corridor.

Based on the evaluation of several scenarios by using a VISISM microsimulation model, this thesis found that the installation of BRT lanes on Michigan Avenue will increase bus travel speed by 21% for both the north and south bound directions in the corridor, and improve the bus reliability (reducing around 10% travel time fluctuation from the mean, compared to the base case). Meanwhile, the implementation of BRT lanes will only reduce the automobile travel speed by 0.6 mph at the whole Loop network level. Thus it ensures the feasibility of the BRT implementation on Michigan Avenue in the Chicago Loop.

This thesis has demonstrated how a microsimulation approach can be used to facilitate transportation planners and policy makers finding ways out of congestion for the Chicago Loop area. By employing the microsimulation model developed in this thesis, more scenarios, such as signal preemption and off-board fare collection for BRT, parking price management and congestion pricing can be tested for future research to assist decision makers on policy making.

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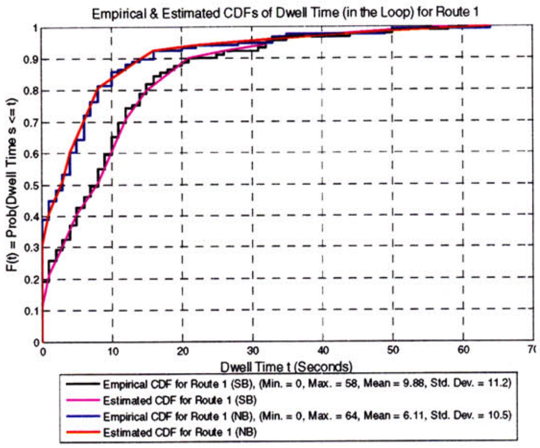
Appendix

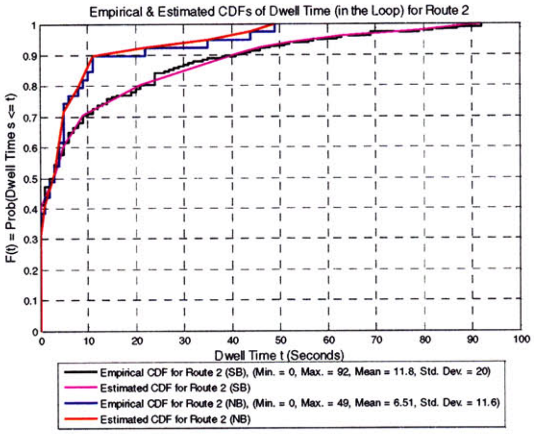
A. MATLAB Codes for Generating the Seed Automobile O-D Matrix

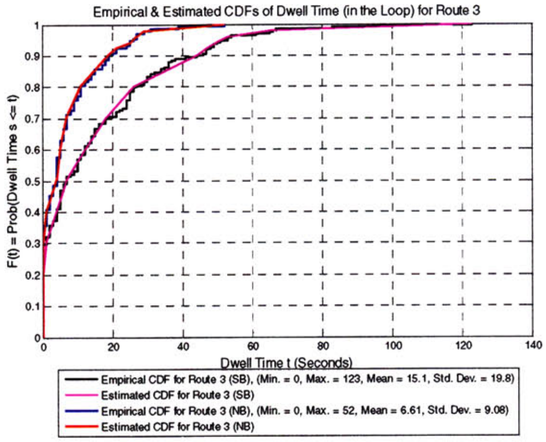
```
-----------------------------------------------------------------------------------
function [Y]=Gen_OD(In, Out, PK, X)
% Main Program
P=ones(127,127);
Y=X;
while ones(1,127)*abs(P)*ones(127,1)>0.1
   Y1=row_op(In, Out, PK, Y);
   Y2=column_op(In, Out, PK, Y1);
   P=Y2-Y;
   P=P(:,2:128);
   Y=Y2;
end
-----------------------------------------------------------------------------------
function [Y]=column_op(In, Out, PK, X)
% Column Operation
Y=X;
j=1;
In_total=ones(1,37)*In(:,2);
PK_total=ones(1,90)*PK(:,2);
In_seed=ones(1,127)*X(:,2:38)*ones(37,1);
In_seed2=ones(1,127)*X(:,39:128)*ones(90,1);
while j<=37
   In_j=ones(1,127)*X(:,j+1);
   if In_j>0
      Y(:,j+1)=X(:,j+1)*(1/37)/(In_j/In_seed);
      Y(:,j+1)=Y(:,j+1)*(In(j,2)/In_total)*37;
   end
   j=j+1;
end
j=1;
while j<=90
   In_j=ones(1,127)*X(:,j+38);
   if In_j>0
      Y(:,j+38)=X(:,j+38)*(1/90)/(In_j/In_seed2);
      Y(:,j+38)=Y(:,j+38)*(PK(j,2)/PK_total)*90;
   end
   j=j+1;
end
-----------------------------------------------------------------------------------
function [Y]=row_op(In, Out, PK, X)
% Row Operation
Y=X;
```

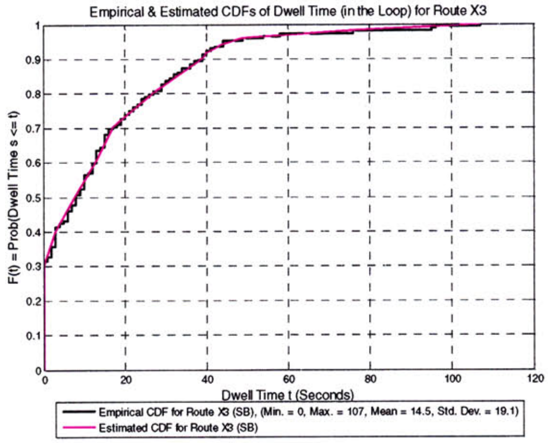
```
j=1;
Out_total=ones(1,37)*Out(:,2);
PK_total=ones(1,90)*PK(:,2);
Out_seed=ones(1,37)*X(1:37,2:128)*ones(127,1);
Out_seed2=ones(1,90)*X(38:127,2:128)*ones(127,1);
while j<=37
   Out_j=X(j,2:128)*ones(127,1);
   if Out_j>0
      Y(j,2:128)=X(j,2:128)*(1/37)/(Out_j/Out_seed);
      Y(j,2:128)=Y(j,2:128)*(Out(j,2)/Out_total)*37;
   end
   j=j+1;
end
j=1;
while j<=90
   Out_j=X(j+37,2:128)*ones(127,1);
   if Out_j>0
      Y(j+37,2:128)=X(j+37,2:128)*(1/90)/(Out_j/Out_seed2);
      Y(j+37,2:128)=Y(j+37,2:128)*(PK(j,2)/PK_total)*90;
   end
   j=j+1;
end
--------------------------------------------------------------------------------------
```

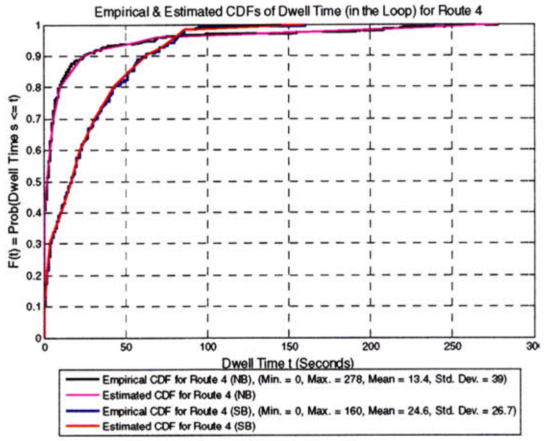
B. Dwell Time CDFs for Each Bus Route Traveling through the Loop

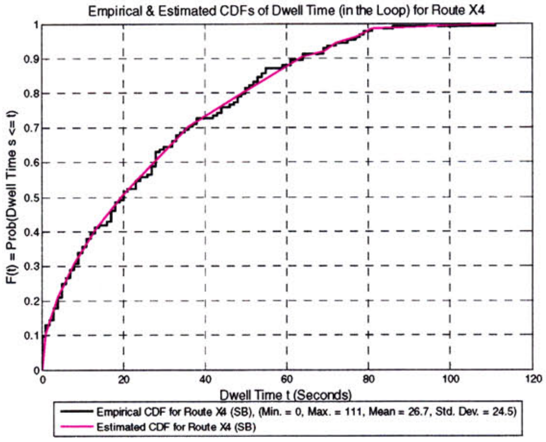


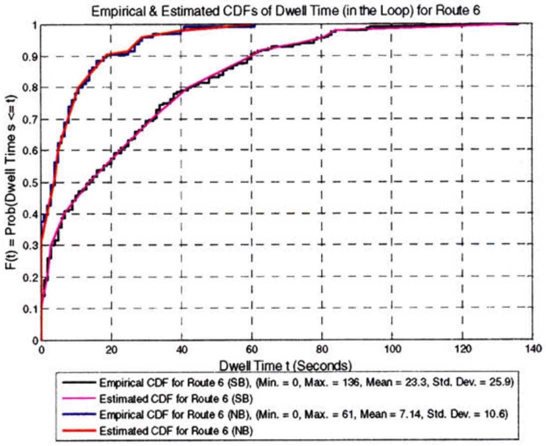


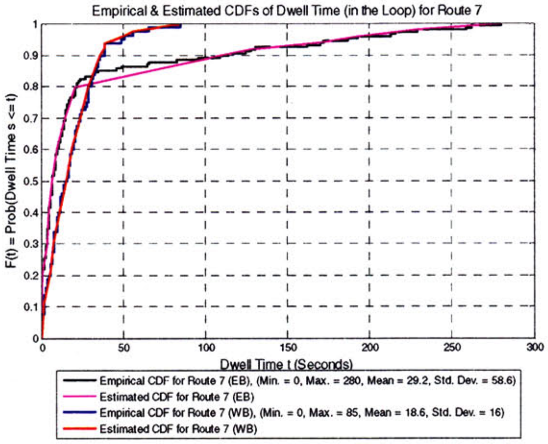


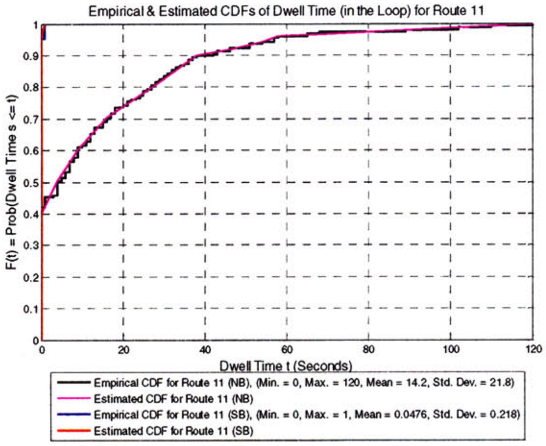


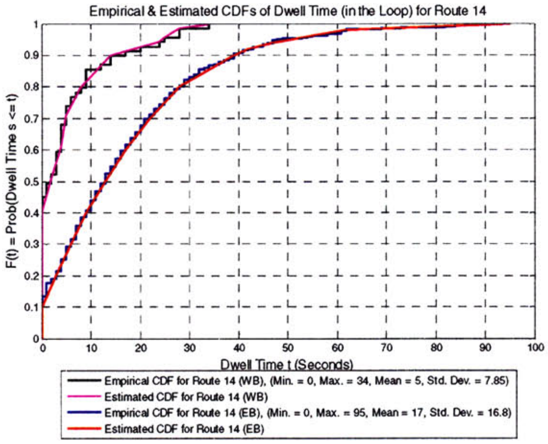


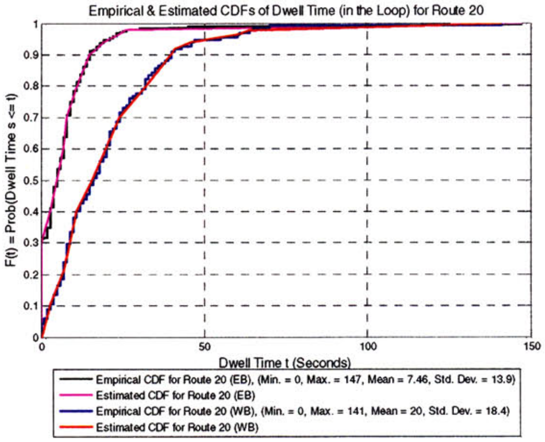


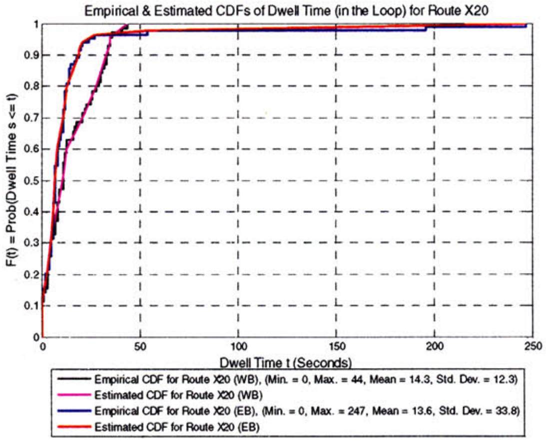

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 6
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140
Empirical CDF for Route 6 (SB), (Min. = 0, Max. = 136, Mean = 23.3, Std. Dev. = 25.9)
Estimated CDF for Route 6 (SB)
Empirical CDF for Route 6 (NB), (Min. = 0, Max. = 61, Mean = 7.14, Std. Dev. = 10.6)
Estimated CDF for Route 6 (NB)

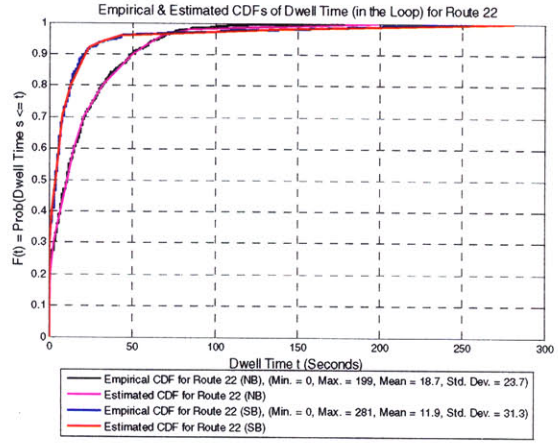

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 7
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
50
100
150
200
250
300
Empirical CDF for Route 7 (EB), (Min. = 0, Max. = 280, Mean = 29.2, Std. Dev. = 58.6)
Estimated CDF for Route 7 (EB)
Empirical CDF for Route 7 (WB), (Min. = 0, Max. = 85, Mean = 18.6, Std. Dev. = 16)
Estimated CDF for Route 7 (WB)

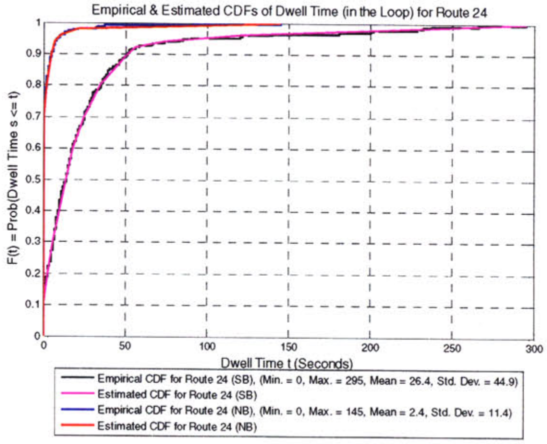

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 11
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
Empirical CDF for Route 11 (NB), (Min. = 0, Max. = 120, Mean = 14.2, Std. Dev. = 21.8)
Estimated CDF for Route 11 (NB)
Empirical CDF for Route 11 (SB), (Min. = 0, Max. = 1, Mean = 0.0476, Std. Dev. = 0.218)
Estimated CDF for Route 11 (SB)

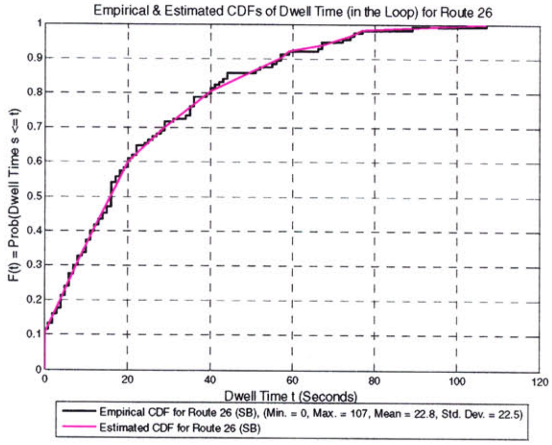

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 14
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100
Empirical CDF for Route 14 (WB), (Min. = 0, Max. = 34, Mean = 5, Std. Dev. = 7.85)
Estimated CDF for Route 14 (WB)
Empirical CDF for Route 14 (EB), (Min. = 0, Max. = 95, Mean = 17, Std. Dev. = 16.8)
Estimated CDF for Route 14 (EB)

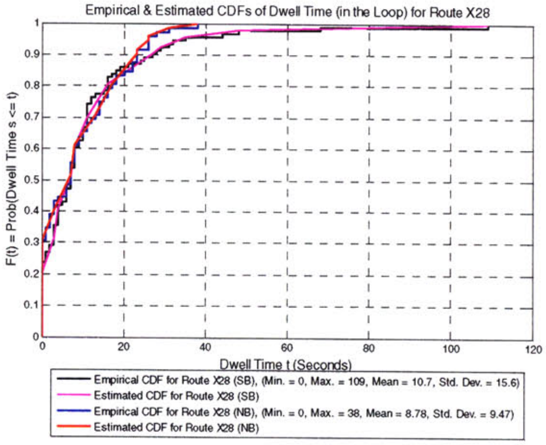

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 20
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
50
100
150
Empirical CDF for Route 20 (EB), (Min. = 0, Max. = 147, Mean = 7.46, Std. Dev. = 13.9)
Estimated CDF for Route 20 (EB)
Empirical CDF for Route 20 (WB), (Min. = 0, Max. = 141, Mean = 20, Std. Dev. = 18.4)
Estimated CDF for Route 20 (WB)

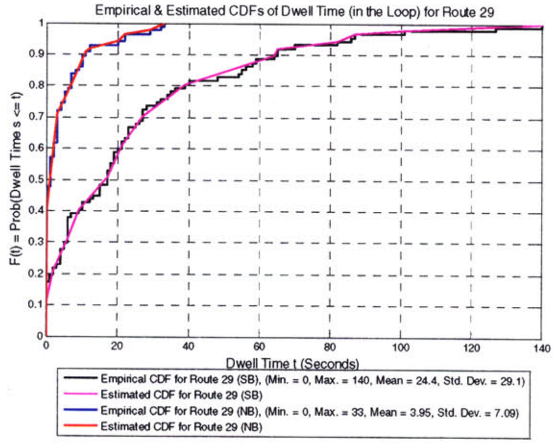

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route X20
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
50
100
150
200
250
Empirical CDF for Route X20 (WB), (Min. = 0, Max. = 44, Mean = 14.3, Std. Dev. = 12.3)
Estimated CDF for Route X20 (WB)
Empirical CDF for Route X20 (EB), (Min. = 0, Max. = 247, Mean = 13.6, Std. Dev. = 33.8)
Estimated CDF for Route X20 (EB)

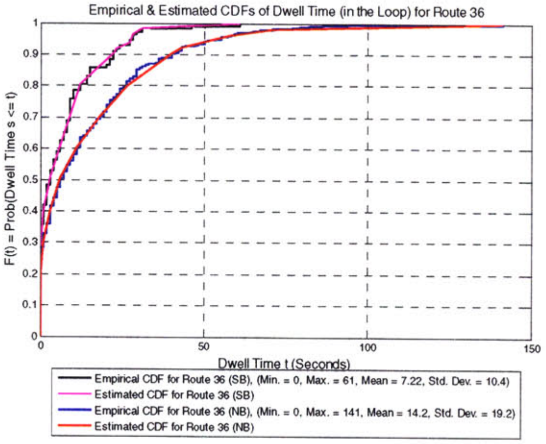

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 22

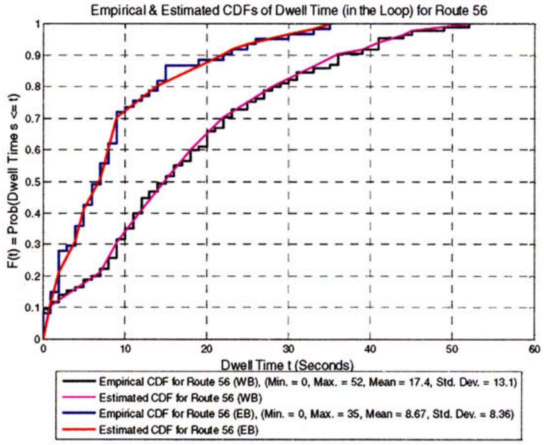

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 24

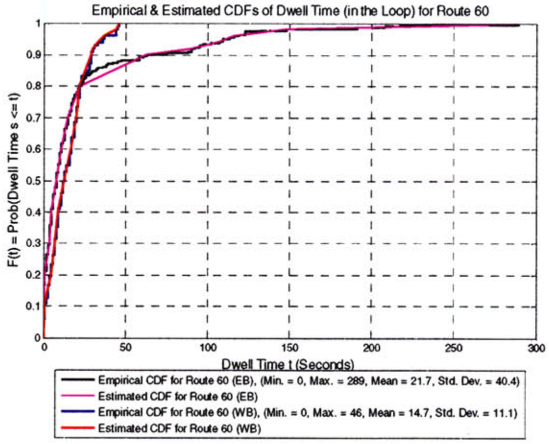

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 26

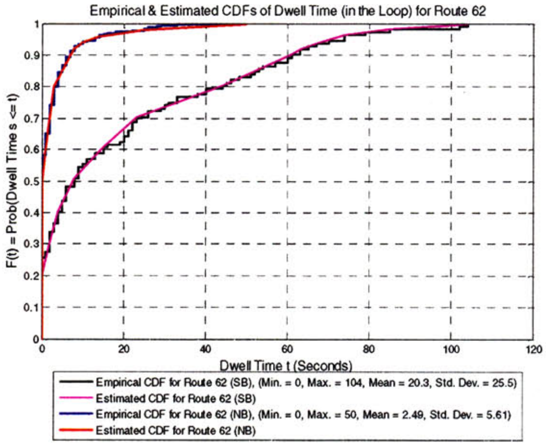

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route X28

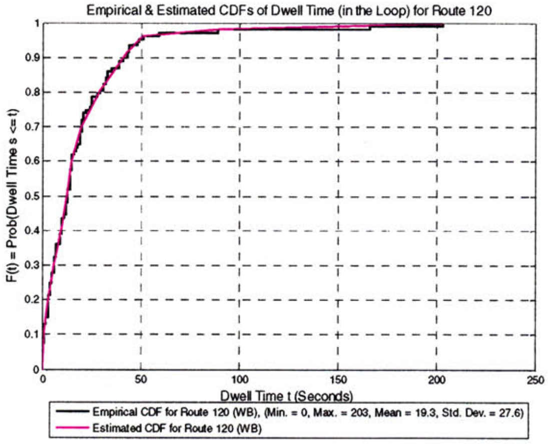

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 29

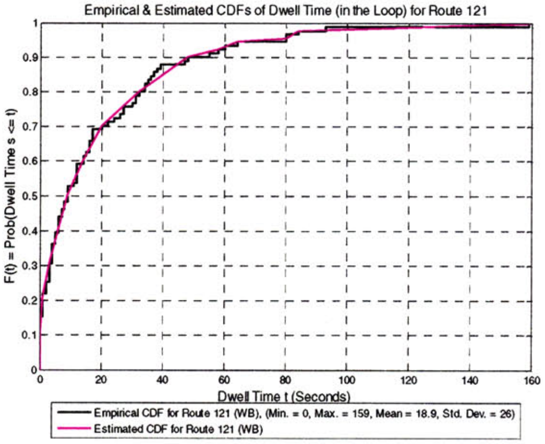

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 36

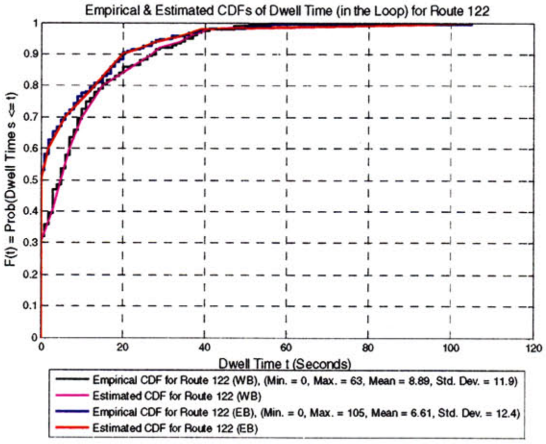

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 56
F(t) = Prob(Dwell Time s <= t)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
Dwell Time t (Seconds)
Empirical CDF for Route 56 (WB), (Min. = 0, Max. = 52, Mean = 17.4, Std. Dev. = 13.1)
Estimated CDF for Route 56 (WB)
Empirical CDF for Route 56 (EB), (Min. = 0, Max. = 35, Mean = 8.67, Std. Dev. = 8.36)
Estimated CDF for Route 56 (EB)

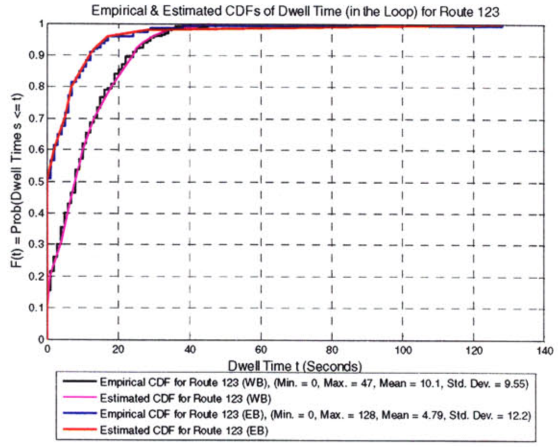

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 60
F(t) = Prob(Dwell Time s <= t)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
50
100
150
200
250
300
Dwell Time t (Seconds)
Empirical CDF for Route 60 (EB), (Min. = 0, Max. = 289, Mean = 21.7, Std. Dev. = 40.4)
Estimated CDF for Route 60 (EB)
Empirical CDF for Route 60 (WB), (Min. = 0, Max. = 46, Mean = 14.7, Std. Dev. = 11.1)
Estimated CDF for Route 60 (WB)

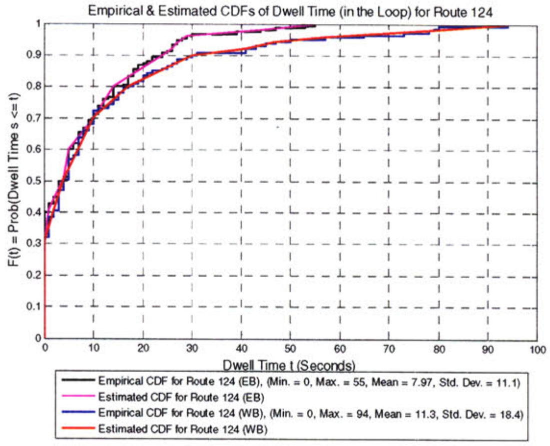

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 62
F(t) = Prob(Dwell Time s <= t)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
Dwell Time t (Seconds)
Empirical CDF for Route 62 (SB), (Min. = 0, Max. = 104, Mean = 20.3, Std. Dev. = 25.5)
Estimated CDF for Route 62 (SB)
Empirical CDF for Route 62 (NB), (Min. = 0, Max. = 50, Mean = 2.49, Std. Dev. = 5.61)
Estimated CDF for Route 62 (NB)

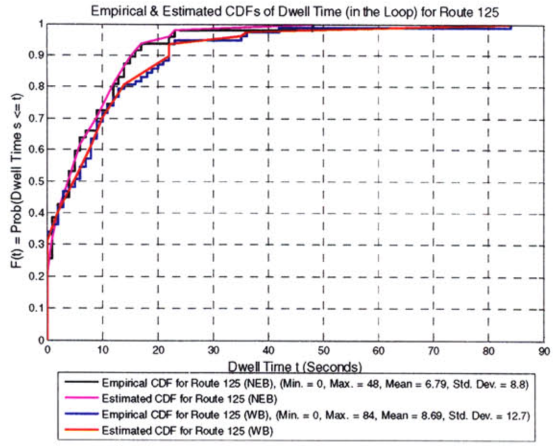

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 120
F(t) = Prob(Dwell Time s <= t)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
50
100
150
200
250
Dwell Time t (Seconds)
Empirical CDF for Route 120 (WB), (Min. = 0, Max. = 203, Mean = 19.3, Std. Dev. = 27.6)
Estimated CDF for Route 120 (WB)

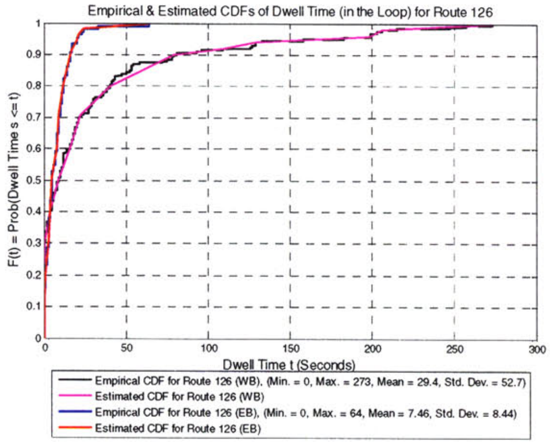

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 121
F(t) = Prob(Dwell Time s <= t)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140
160
Dwell Time t (Seconds)
Empirical CDF for Route 121 (WB), (Min. = 0, Max. = 159, Mean = 18.9, Std. Dev. = 26)
Estimated CDF for Route 121 (WB)

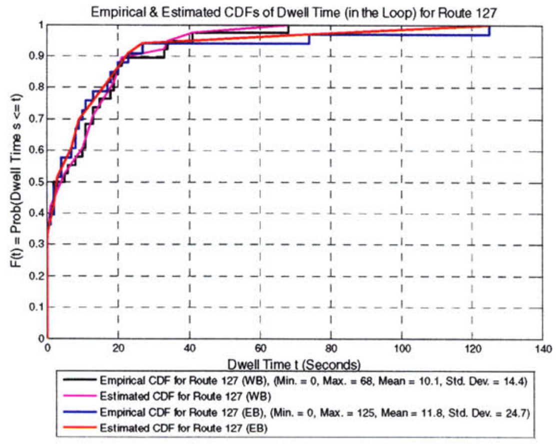

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 122
F(t) = Prob(Dwell Time s <= t)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
Dwell Time t (Seconds)
Empirical CDF for Route 122 (WB), (Min. = 0, Max. = 63, Mean = 8.89, Std. Dev. = 11.9)
Estimated CDF for Route 122 (WB)
Empirical CDF for Route 122 (EB), (Min. = 0, Max. = 105, Mean = 6.61, Std. Dev. = 12.4)
Estimated CDF for Route 122 (EB)

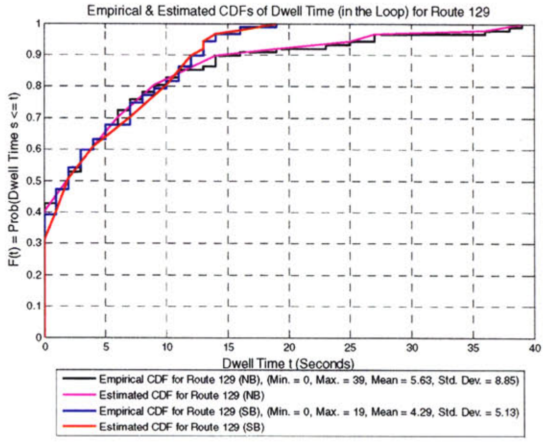

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 123
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140
Empirical CDF for Route 123 (WB), (Min. = 0, Max. = 47, Mean = 10.1, Std. Dev. = 9.55)
Estimated CDF for Route 123 (WB)
Empirical CDF for Route 123 (EB), (Min. = 0, Max. = 128, Mean = 4.79, Std. Dev. = 12.2)
Estimated CDF for Route 123 (EB)

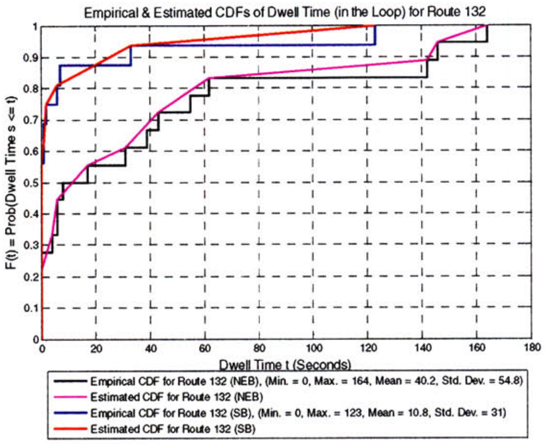

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 124
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100
Empirical CDF for Route 124 (EB), (Min. = 0, Max. = 55, Mean = 7.97, Std. Dev. = 11.1)
Estimated CDF for Route 124 (EB)
Empirical CDF for Route 124 (WB), (Min. = 0, Max. = 94, Mean = 11.3, Std. Dev. = 18.4)
Estimated CDF for Route 124 (WB)

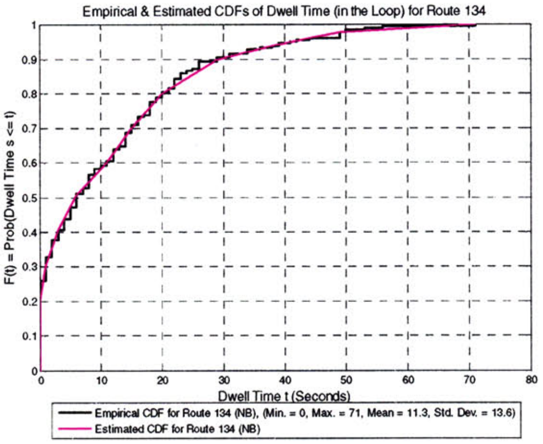

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 125
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
Empirical CDF for Route 125 (NEB), (Min. = 0, Max. = 48, Mean = 6.79, Std. Dev. = 8.8)
Estimated CDF for Route 125 (NEB)
Empirical CDF for Route 125 (WB), (Min. = 0, Max. = 84, Mean = 8.69, Std. Dev. = 12.7)
Estimated CDF for Route 125 (WB)

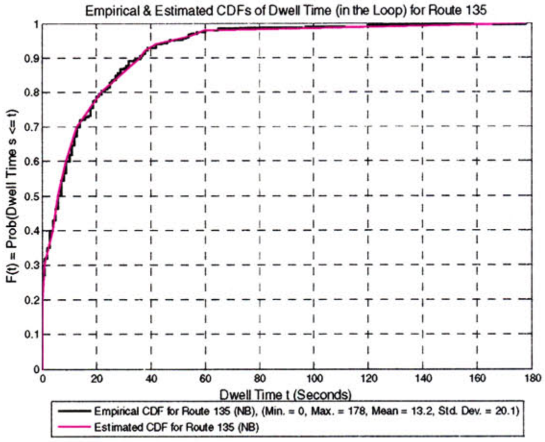

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 126
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
50
100
150
200
250
300
Empirical CDF for Route 126 (WB), (Min. = 0, Max. = 273, Mean = 29.4, Std. Dev. = 52.7)
Estimated CDF for Route 126 (WB)
Empirical CDF for Route 126 (EB), (Min. = 0, Max. = 64, Mean = 7.46, Std. Dev. = 8.44)
Estimated CDF for Route 126 (EB)

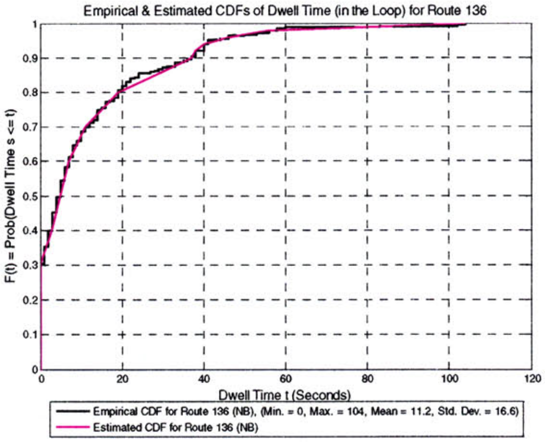

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 127
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140
Empirical CDF for Route 127 (WB), (Min. = 0, Max. = 68, Mean = 10.1, Std. Dev. = 14.4)
Estimated CDF for Route 127 (WB)
Empirical CDF for Route 127 (EB), (Min. = 0, Max. = 125, Mean = 11.8, Std. Dev. = 24.7)
Estimated CDF for Route 127 (EB)

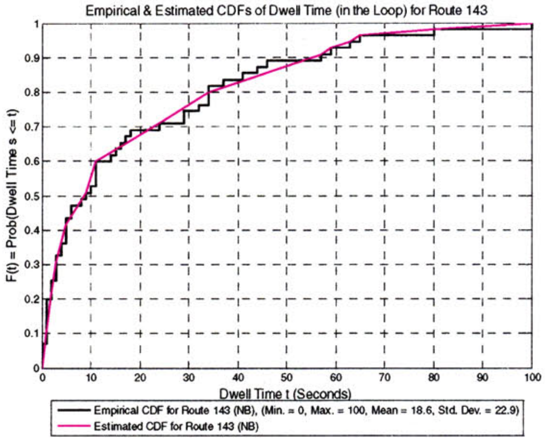

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 129
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
30
35
40
Empirical CDF for Route 129 (NB), (Min. = 0, Max. = 39, Mean = 5.63, Std. Dev. = 8.85)
Estimated CDF for Route 129 (NB)
Empirical CDF for Route 129 (SB), (Min. = 0, Max. = 19, Mean = 4.29, Std. Dev. = 5.13)
Estimated CDF for Route 129 (SB)

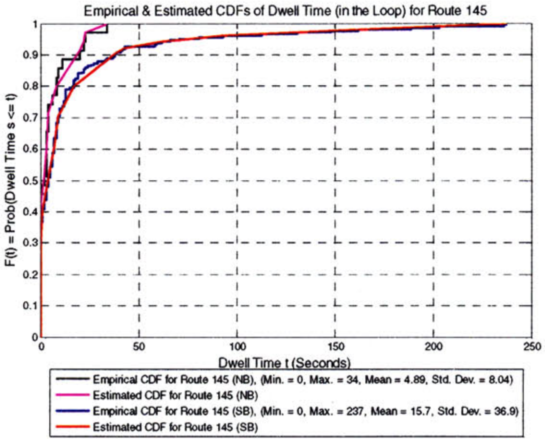

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 132
F(t) = Prob(Dwell Time s <= t)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140
160
180
Dwell Time t (Seconds)
Empirical CDF for Route 132 (NEB), (Min. = 0, Max. = 164, Mean = 40.2, Std. Dev. = 54.8)
Estimated CDF for Route 132 (NEB)
Empirical CDF for Route 132 (SB), (Min. = 0, Max. = 123, Mean = 10.8, Std. Dev. = 31)
Estimated CDF for Route 132 (SB)

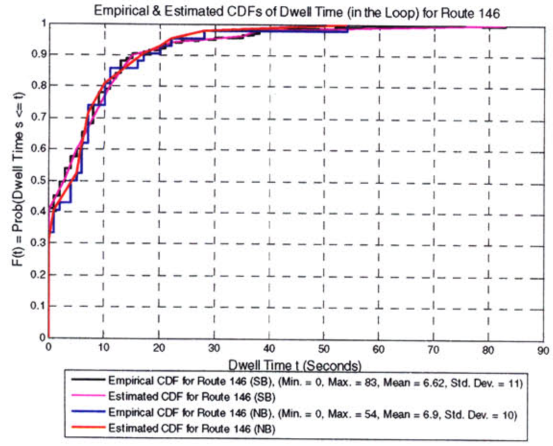

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 134
F(t) = Prob(Dwell Time s <= t)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
Dwell Time t (Seconds)
Empirical CDF for Route 134 (NB), (Min. = 0, Max. = 71, Mean = 11.3, Std. Dev. = 13.6)
Estimated CDF for Route 134 (NB)

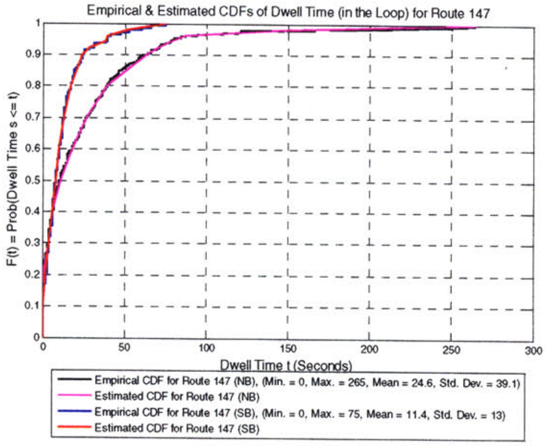

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 135
F(t) = Prob(Dwell Time s <= t)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140
160
180
Dwell Time t (Seconds)
Empirical CDF for Route 135 (NB), (Min. = 0, Max. = 178, Mean = 13.2, Std. Dev. = 20.1)
Estimated CDF for Route 135 (NB)

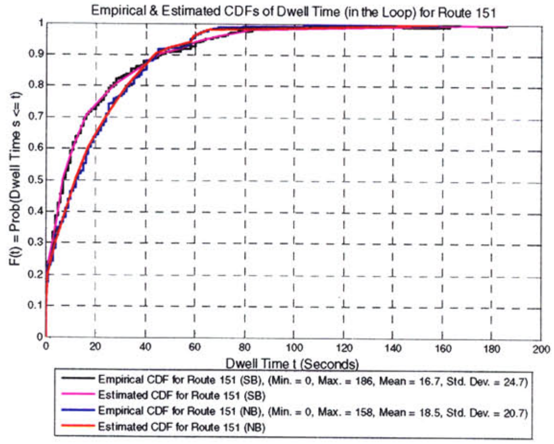

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 136
F(t) = Prob(Dwell Time s <= t)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
Dwell Time t (Seconds)
Empirical CDF for Route 136 (NB), (Min. = 0, Max. = 104, Mean = 11.2, Std. Dev. = 16.6)
Estimated CDF for Route 136 (NB)

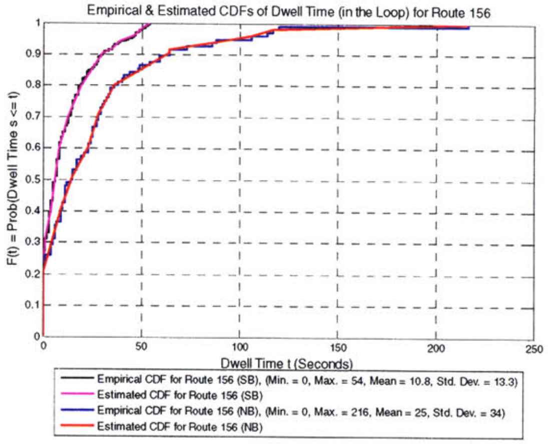

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 143
F(t) = Prob(Dwell Time s <= t)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100
Dwell Time t (Seconds)
Empirical CDF for Route 143 (NB), (Min. = 0, Max. = 100, Mean = 18.6, Std. Dev. = 22.9)
Estimated CDF for Route 143 (NB)

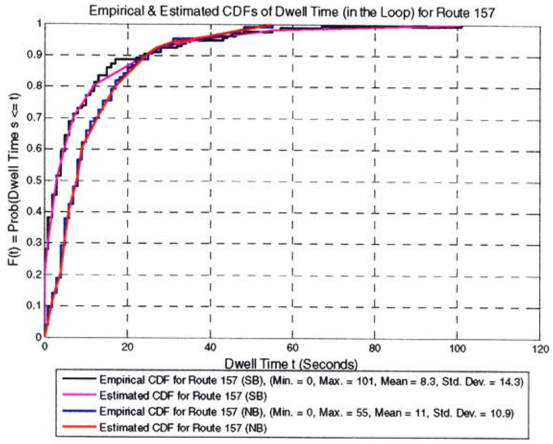

Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 145
F(t) = Prob(Dwell Time s <= t)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
50
100
150
200
250
Dwell Time t (Seconds)
Empirical CDF for Route 145 (NB), (Min. = 0, Max. = 34, Mean = 4.89, Std. Dev. = 8.04)
Estimated CDF for Route 145 (NB)
Empirical CDF for Route 145 (SB), (Min. = 0, Max. = 237, Mean = 15.7, Std. Dev. = 36.9)
Estimated CDF for Route 145 (SB)


Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 146
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
Empirical CDF for Route 146 (SB), (Min. = 0, Max. = 83, Mean = 6.62, Std. Dev. = 11)
Estimated CDF for Route 146 (SB)
Empirical CDF for Route 146 (NB), (Min. = 0, Max. = 54, Mean = 6.9, Std. Dev. = 10)
Estimated CDF for Route 146 (NB)


Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 147
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
50
100
150
200
250
300
Empirical CDF for Route 147 (NB), (Min. = 0, Max. = 265, Mean = 24.6, Std. Dev. = 39.1)
Estimated CDF for Route 147 (NB)
Empirical CDF for Route 147 (SB), (Min. = 0, Max. = 75, Mean = 11.4, Std. Dev. = 13)
Estimated CDF for Route 147 (SB)


Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 151
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140
160
180
200
Empirical CDF for Route 151 (SB), (Min. = 0, Max. = 186, Mean = 16.7, Std. Dev. = 24.7)
Estimated CDF for Route 151 (SB)
Empirical CDF for Route 151 (NB), (Min. = 0, Max. = 158, Mean = 18.5, Std. Dev. = 20.7)
Estimated CDF for Route 151 (NB)


Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 156
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
50
100
150
200
250
Empirical CDF for Route 156 (SB), (Min. = 0, Max. = 54, Mean = 10.8, Std. Dev. = 13.3)
Estimated CDF for Route 156 (SB)
Empirical CDF for Route 156 (NB), (Min. = 0, Max. = 216, Mean = 25, Std. Dev. = 34)
Estimated CDF for Route 156 (NB)


Empirical & Estimated CDFs of Dwell Time (in the Loop) for Route 157
F(t) = Prob(Dwell Time s <= t)
Dwell Time t (Seconds)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
Empirical CDF for Route 157 (SB), (Min. = 0, Max. = 101, Mean = 8.3, Std. Dev. = 14.3)
Estimated CDF for Route 157 (SB)
Empirical CDF for Route 157 (NB), (Min. = 0, Max. = 55, Mean = 11, Std. Dev. = 10.9)
Estimated CDF for Route 157 (NB)

C. Dwell Time Models for Testing Stop Location Effects

Model 1:
Dwell Time =f(FOn, FOff, ROff, PassLoad, Dum_Mich)

Descriptive Statistics

	Mean	Std. Deviation	N
Dwell Time	15.06	15.701	2866
FOn	3.20	3.804	2866
FOff	1.00	1.624	2866
ROff	.79	1.566	2866
PassLoad	25.06	17.967	2866
Dum_Mich	.27	.446	2866

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Dum_Mich , ROff , PassLoad, FOn , FOff[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Dwell Time

Model Summary[b]

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	.862[a]	.743	.743	7.963	.743	1655.564	5	2860	.000

a. Predictors: (Constant), Dum_Mich , ROff , PassLoad, FOn , FOff

b. Dependent Variable: Dwell Time

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	524929.9	5	104985.979	1655.564	.000[a]
	Residual	181364.1	2860	63.414		
	Total	706294.0	2865			

a. Predictors: (Constant), Dum_Mich , ROff , PassLoad, FOn , FOff

b. Dependent Variable: Dwell Time

Coefficients[a]

		Unstandardized Coefficients		Standardized Coefficients		
Model		B	Std. Error	Beta	t	Sig.
1	(Constant)	.817	.303		2.693	.007
	FOn	3.643	.042	.882	87.278	.000
	FOff	1.668	.107	.173	15.519	.000
	ROff	.882	.110	.088	7.992	.000
	PassLoad	-.013	.009	-.015	-1.515	.130
	Dum_Mich	1.961	.337	.056	5.822	.000

a. Dependent Variable: Dwell Time

Model 2:
Dwell Time =f(FOn, FOff, ROff, PassLoad, Dum_Mich, Dum_State)

Descriptive Statistics

	Mean	Std. Deviation	N
Dwell Time	15.06	15.701	2866
FOn	3.20	3.804	2866
FOff	1.00	1.624	2866
ROff	.79	1.566	2866
PassLoad	25.06	17.967	2866
Dum_Mich	.27	.446	2866
Dum_State	.09	.288	2866

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Dum_ State, FOff , PassLoad, Dum_Mich , FOn, ROff[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Dwell Time

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.863[a]	.746	.745	7.928	.746	1396.456	6	2859	.000

a. Predictors: (Constant), Dum_State, FOff , PassLoad, Dum_Mich , FOn , ROff

b. Dependent Variable: Dwell Time

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	526605.2	6	87767.539	1396.456	.000[a]
	Residual	179688.7	2859	62.850		
	Total	706294.0	2865			

a. Predictors: (Constant), Dum_State, FOff , PassLoad, Dum_Mich , FOn , ROff

b. Dependent Variable: Dwell Time

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.580	.306		1.898	.058
	FOn	3.628	.042	.879	87.108	.000
	FOff	1.651	.107	.171	15.424	.000
	ROff	.881	.110	.088	8.019	.000
	PassLoad	-.015	.009	-.017	-1.701	.089
	Dum_Mich	2.304	.342	.065	6.740	.000
	Dum_State	2.720	.527	.050	5.163	.000

a. Dependent Variable: Dwell Time

Model 3:
Dwell Time =f(FOn, FOff, ROff, PassLoad, Dum_Mich, Dum_State, Dum_Wash, Dum_Madi)

Descriptive Statistics

	Mean	Std. Deviation	N
Dwell Time	15.06	15.701	2866
FOn	3.20	3.804	2866
FOff	1.00	1.624	2866
ROff	.79	1.566	2866
PassLoad	25.06	17.967	2866
Dum_Mich	.27	.446	2866
Dum_State	.09	.288	2866
Dum_Wash	.11	.307	2866
Dum_Madi	.06	.233	2866

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Dum_Madi , ROff , PassLoad, Dum_ State, Dum_ Wash , FOn , Dum_Mich , FOff[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Dwell Time

Model Summary[b]

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	.864[a]	.747	.746	7.912	.747	1053.126	8	2857	.000

a. Predictors: (Constant), Dum_Madi , ROff , PassLoad, Dum_State, Dum_Wash , FOn , Dum_Mich , FOff

b. Dependent Variable: Dwell Time

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	527435.6	8	65929.444	1053.126	.000[a]
	Residual	178858.4	2857	62.604		
	Total	706294.0	2865			

a. Predictors: (Constant), Dum_Madi , ROff , PassLoad, Dum_State, Dum_Wash , FOn , Dum_Mich , FOff

b. Dependent Variable: Dwell Time

Coefficients[a]

		Unstandardized Coefficients		Standardized Coefficients		
Model		B	Std. Error	Beta	t	Sig.
1	(Constant)	.334	.318		1.048	.295
	FOn	3.639	.042	.882	87.135	.000
	FOff	1.619	.107	.168	15.077	.000
	ROff	.826	.111	.082	7.464	.000
	PassLoad	-.019	.009	-.021	-2.142	.032
	Dum_Mich	2.711	.361	.077	7.500	.000
	Dum_State	3.104	.538	.057	5.772	.000
	Dum_Wash	1.875	.521	.037	3.598	.000
	Dum_Madi	.711	.655	.011	1.086	.278

a. Dependent Variable: Dwell Time

D. MATLAB Codes for Plotting Figure 5-3

```
[N C]=size(NewDwellNum);
Dum_Mich=zeros(N,1);
Dum_State=zeros(N,1);
Dum_Madi=zeros(N,1);
Dum_Wash=zeros(N,1);
Y=NewDwellNum(:,7);
FOn=NewDwellNum(:,8);
FOff=NewDwellNum(:,10);
ROff=NewDwellNum(:,11);
PassLoad=NewDwellNum(:,12);
Const=ones(N,1);
[N_Madi C]=size(MadisonStopNum);
i=1;
while i<=N_Madi
        k=1;
        while k<=N
                if MadisonStopNum(i,1)==NewDwellNum(k,5)
                        Dum_Madi(k,1)=1;
                end
                k=k+1;
        end
        i=i+1;
end
[N_Mich C]=size(MichiganStopNum);
i=1;
while i<=N_Mich
        k=1;
        while k<=N
                if MichiganStopNum(i,1)==NewDwellNum(k,5)
                        Dum_Mich(k,1)=1;
                end
                k=k+1;
        end
        i=i+1;
end
[N_State C]=size(StateStopNum);
i=1;
while i<=N_State
        k=1;
        while k<=N
                if StateStopNum(i,1)==NewDwellNum(k,5)
                        Dum_State(k,1)=1;
                end
                k=k+1;
```

```
        end
        i=i+1;
end
[N_Wash C]=size(WashingtonStopNum);
i=1;
while i<=N_Wash
        k=1;
        while k<=N
                if WashingtonStopNum(i,1)==NewDwellNum(k,5)
                        Dum_Wash(k,1)=1;
                end
                k=k+1;
        end
        i=i+1;
end
% So far, the dummy variables are defined.
StopID_Mich=MichiganStopNum;
[m c]=size(StopID_Mich);
i=m;
while i>=1
        count=0;
        StopID=StopID_Mich(i,1);
        k=1;
        while k<=N
                if StopID==NewDwellNum(k,5)&&1==Dum_Mich(k,1)
                        count=count+1;
                end
        k=k+1;
        end
        if count==0
                StopID_Mich(i,:)=[];
        end
        i=i-1;
end
% So far, those stops on Mich. Ave. which are far from satellites are selected and stored in
StopID_Mich.
BusID=ones(N,1);
i=2;
while i<=N+1
        BusID(i-1,1)=str2num(cell2mat(NewDwellTxt(i,6)));
        i=i+1;
end
NewDwellData=[NewDwellNum(:,1) NewDwellNum(:,3) NewDwellNum(:,5) BusID
NewDwellNum(:,7:12)];
% NewDwellData
% =[Day Time(Abs._seconds) Stop_ID Bus_ID Dwell_Time FOn ROn FOff ROff
Passenger_Load], no Route_ID in this matrix.
```

```
% NewDwellData has become the basic and convenient data now.
Data=[NewDwellData Dum_Mich zeros(N,1)]; % "Data" is the matrix to store stay time info.
("Dum_Mich" is an indicator for Mich. Ave.)
time=1;
[M c]=size(Data);
while time<=2
        [M c]=size(Data);
        i=M;
        while i>=1
                j=i-1;
                while j>=1
                        if
Data(j,1)==Data(i,1)&&Data(j,3)==Data(i,3)&&Data(j,4)==Data(i,4)&&abs(Data(j,2)-
Data(i,2))<=1200
                                if Data(j,2)==Data(i,2)
                                        display('Duplicate Record.')
                                        if Data(j,5)>=Data(i,5)
                                                Data(i,:)=[];
                                        else
                                                Data(j,:)=[];
                                        end
                                        i=i-1;
                                        Data=Data;
                                end
                                if Data(j,2)>Data(i,2)
                                        t0=min(Data(i,2),Data(j,2));
                                        t1=max(Data(i,2)+Data(i,5),Data(j,2)+Data(j,5));
                                        Data(i,5)=t1-t0;
                                        Data(j,:)=[];
                                        i=i-1;
                                end
                                if Data(i,2)>Data(j,2)
                                        t0=min(Data(i,2),Data(j,2));
                                        t1=max(Data(i,2)+Data(i,5),Data(j,2)+Data(j,5));
                                        Data(j,5)=t1-t0;
                                        Data(i,:)=[];
                                        i=i-1;
                                end
                        end
                        j=j-1;
                end
                i=i-1;
        end
        time=time+1;
end
[M c]=size(Data);
i=1;
```

```
while i<=M
    j=i+1;
    while j<=M
        if
Data(j,1)==Data(i,1)&&Data(j,3)==Data(i,3)&&((Data(i,2)<=Data(j,2)+Data(j,5)&&Data(i,2)>=Da
ta(j,2)) | (Data(j,2)<=Data(i,2)+Data(i,5)&&Data(j,2)>=Data(i,2)))
            if Data(j,2)<Data(i,2)
                Data(i,12)=1;
            end
            if Data(i,2)<Data(j,2)
                Data(j,12)=1;
            end
            if Data(j,2)==Data(i,2)
                if Data(j,5)>=Data(i,5)
                    Data(j,12)=1;
                else
                    Data(i,12)=1;
                end
            end
        end
        j=j+1;
    end
    i=i+1;
end
pileup_stay_time=Data(:,5);
pileup_stay_time(find(Data(:,12)==0))=[];
nopileup_stay_time=Data(:,5);
nopileup_stay_time(find(Data(:,12)==1))=[];
[M c]=size(pileup_stay_time);
i=M;
while i>=1
    if pileup_stay_time(i,1)<1 | pileup_stay_time(i,1)>600
        pileup_stay_time(i,:)=[];
    end
    i=i-1;
end
[M c]=size(nopileup_stay_time);
i=M;
while i>=1
    if nopileup_stay_time(i,1)<1 | nopileup_stay_time(i,1)>600
        nopileup_stay_time(i,:)=[];
    end
    i=i-1;
end
info=[min(pileup_stay_time) max(pileup_stay_time) mean(pileup_stay_time)
std(pileup_stay_time)
```

```
    min(nopileup_stay_time) max(nopileup_stay_time) mean(nopileup_stay_time)
std(nopileup_stay_time)];
% The following is the No-Max Version (The previous version set 600 seconds as the upper
limit.):
pileup_stay_time=Data(:,5);
pileup_stay_time(find(Data(:,12)==0))=[];
nopileup_stay_time=Data(:,5);
nopileup_stay_time(find(Data(:,12)==1))=[];
[M c]=size(pileup_stay_time);
i=M;
while i>=1
        if pileup_stay_time(i,1)<1
                pileup_stay_time(i,:)=[];
        end
        i=i-1;
end
[M c]=size(nopileup_stay_time);
i=M;
while i>=1
        if nopileup_stay_time(i,1)<1
                nopileup_stay_time(i,:)=[];
        end
        i=i-1;
end
info=[min(pileup_stay_time) max(pileup_stay_time) mean(pileup_stay_time)
std(pileup_stay_time)
    min(nopileup_stay_time) max(nopileup_stay_time) mean(nopileup_stay_time)
std(nopileup_stay_time)];
% Pix drawing program is compiled below:
h1=cdfplot(pileup_stay_time)
set(h1,'Color',[0 0 1],'LineWidth',2);
hold on
h2=cdfplot(nopileup_stay_time)
set(h2,'Color',[1 0 0],'LineWidth',2);
h=[h1 h2];
name1=['CDF of Stay Time When Pileup Happens (Min. = ',num2str(info(1,1),3),', Max. =
',num2str(info(1,2),3),', Mean = ',num2str(info(1,3),3),', Std. Dev. = ',num2str(info(1,4),3),')'];
name2=['CDF of Stay Time When There Is No Pileup (Min. = ',num2str(info(2,1),3),', Max. =
',num2str(info(2,2),3),', Mean = ',num2str(info(2,3),3),', Std. Dev. = ',num2str(info(2,4),3),')'];
legend(name1,name2,'Location','SouthOutside');
title1=cellstr('Empirical CDFs of Bus Stay Time at Given Bus Stops In Downtown Chicago in
P.M. Peak on Weekdays');
title2=cellstr('When There Is/Is Not a Pileup (Slack Time = 0 Second)');
title_full=[title1;title2];
                title(title_full,'FontSize',12)
                xlabel('Stay Time at Given Bus Stops in P.M. Peak on Weekdays','FontSize',12)
                ylabel('F(t) = Prob(Stay Time <= t)','FontSize',12)
```

```
filename='CDFs for Stay Time (0 Seconds)';
print('-dmeta',filename)
```