A Microscopic Simulation Laboratory for Advanced Public Transportation System Evaluation

by

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Submitted to the Department of Civil and Environmental Engineering in partial fulfillment of the requirements for the degree of

Master of Science in Transportation

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2002

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Abstract

This thesis sets forth the implementation of bus transit operations models in a microscopic traffic simulation laboratory for the purpose of developing the laboratory's capacity for simulating advanced public transportation systems (APTS). The simulation laboratory used in the research effort is MITSIMLab, a microscopic traffic simulation laboratory developed for the design and evaluation of dynamic traffic management strategies.

The purpose of this research is to develop a tool that may be used to simulate APTS and to evaluate their performance at an operational level. A schedule-based bus supply model and detailed dwell time models were implemented in order to represent the realistic movements of buses about the network in performance of their assigned tasks. The integration of the bus operations models with the existing traffic models in MITSIMLab makes it possible to simulate the interactions between various modes of urban transport and between the transit system and its users. By capturing these complex interactions, MITSIMLab can be used to simulate observed bus transit phenomena, such as bus bunching, and estimate their impacts on system-level and/or passenger-level measures of performance.

The transit models also simulate the generation and distribution of real-time bus operations data from field-deployed technologies such as Automated Vehicle Location (AVL) and automatic passenger counters. Thus, with the addition of the bus operations models, the simulation laboratory may be used to simulate a variety of APTS control strategies, such as conditional bus signal priority, that require real-time data as input. The modular structure of the models allows for the simulation of future APTS technologies as they emerge. A case study of an urban arterial network in Stockholm, Sweden, was conducted in order to demonstrate the capabilities of the bus operations models. The case study is designed to evaluate conditional bus signal priority strategies to quantify the expected impacts of the strategies on both the transit riders and on traffic in the network.

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Acknowledgements

I share credit for this thesis and for my work over the past two years at MIT with a host of groups and individuals, but assume sole ownership of all blunders, oversights and errors herein.

First, I hold the utmost respect and gratitude for my advisors, Moshe Ben-Akiva and Haris Koutsopoulos, for sharing their respective gifts, arts, and skills of teaching. I am grateful to Moshe for his constant sense of humor, even if at our expense, when our workload did not warrant one. To Haris, special thanks is due for his long hours and tireless technical prowess. I only hope that some of their collective genius has rubbed off on me and precipitated onto the pages of this thesis.

Very special thanks go to my friends in the ITS lab. Thanks to Tomer Toledo for his reassuring indifference, the crutch of ITS Lab sanity, in the face of sheer, wanton amounts of work. Thanks to Margaret Cortes for her technical aid, friendship and example – and for being the pinnacle of work/play balance in the lab. I don't know how she does it. Thanks to Angus Davol for paving the way in MITSIMLab and making this thesis possible. Thanks to everyone else in the ITS lab, Constantinos Antoniou, Rama Balakrishnan, Josef Brandriss, Deepak Darda, Kunal Kunde, Manish Mehta, Srinivasan Sundaram, and Zhili Tian, for bearing the load with me, and, in the case of computer difficulties, bearing the load *for* me.

I thank the rest of the transportation students, especially those who started and finished this program with me. Special thanks to Meredith Coley, whom I adore, for being my pain and my peace.

Thanks also to the CTS faculty and adminstrative staff, especially Nigel Wilson for his wise and encouraging academic advice and Leanne Russell her kind support.

Finally, my greatest thanks and appreciation go to my family. A thousand thanks to my parents. Their permanent love and support has been at arm's length throughout, even between Massachusetts and Texas. I thank my father for his unfailing wisdom and guidance, my mother for her caring and strength, my brother, Doug, and sister, Melinda, for their friendship.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The purpose of this thesis is to develop a microscopic traffic simulation tool for the evaluation of bus transit operations and Advanced Public Transportation Systems (APTS) and, in doing so, to provide a tool that is useful to researchers and public transport service providers alike. The research effort described in this thesis involves the incorporation of the most current models of bus transit operations into a previously existing microscopic simulation model. These models are intended to support the simulation of various existing and emerging APTS solutions. The growing attention to, and increasing adoption of, new technologies in public transportation is evidence of the need for such a tool.

As user demand for a transportation system outgrows the system's capacity, and the performance of the system necessarily degrades, transportation planners, policy-makers and engineers, as evidenced in recent years, often look to technology for solutions. This growing emphasis on technology has accelerated the emergence of Intelligent Transportation Systems (ITS). ITS refer to any application of technology (e.g. information technology, communication technology, and sensor technology) to transportation systems in order to better manage the available transportation resources (e.g. capacity, revenue). Slow to gain acceptance and support during the early years that followed its conception, ITS has since garnered widespread support from professionals in all modes and disciplines of transportation.

Driving the need for ITS in an urban transportation context is the lack of land, money, and/or political or public support to build more roads to meet a rising, seemingly boundless, demand for travel by private automobile. ITS provide innovative opportunities to use communications, sensor, information and other technologies to manage the supply and demand for a transportation system in such a way that improves, or optimizes, the performance of the system.

However promising or innovative an ITS solution to urban transportation woes might be, in order for an alternative to be feasible, it must be three things: affordable, available and useful. For the purposes of this thesis, let us consider public transportation in the United States. Under-funded, under-patronized public transit service providers are especially sensitive to the first criterion, affordability. With its diminutive market share of urban travel, public transport has seen little opportunity to win the commuting public's favor, and it's patronage, and thus to effect a positive change in the modern urban decline into congestion and pollution. High operating, maintenance and staffing costs, combined with low ridership, and thus low revenue, and unrelenting competition from the private automobile, have lead to perpetually poor service quality and a subsequent slump in ridership.

Availability, the second criterion for accepting a new technology, is linked to affordability. In general, a product will not become available to any market before the technology upon which it relies has reasonably matured to the point that it is worth the developer's investment. Public transportation agencies in the United States, with limited budgets and minimal public and political support, have never been strong financial sponsors of innovation. However, due to interest from a broad range of science and technology disciplines in communication, information, sensor and other technologies, the cost of ITS technologies has declined, and their availability has thus become more prevalent. For public agencies, however, the cost of ITS technologies is still a formidable constraint. Furthermore, the reluctance to accept new technologies is due, in part, to the fact that the benefits, or returns on the investment, are as yet unproven.

Reluctance to accept untried, untested ITS applications in public transportation speaks to the third criterion, usefulness, and introduces the need for the object of this thesis. It is not clear which benefits, or how said benefits, will be realized from the

adoption of emerging ITS applications in public transit such as automated vehicle location (AVL). It is also not apparent how, and with what effects, these new technologies will interface with the user organization and with the customers. Traffic simulation has long been a tool for evaluating the impacts of alternative roadway geometry and traffic control designs. In recent years, however, there has been growing attention among researchers to the development of simulation tools capable of representing the dynamics of ITS at the operational level and of representing user response to ITS. Few simulators exist that are capable of accurately representing transit operations and interactions between different modes of urban transportation (e.g. bus and car). The design of this thesis, then, is to exploit the usefulness of simulation as an indispensable means of demonstrating the expected benefits of, and thus justifying substantial investments in, new technologies in public transportation.

1.1 Objectives

The objective of this research is to develop a tool that can be used to evaluate the benefits of APTS strategies and, thus, to assist bus transit service provider decision-making with regard to the implementation of intelligent transportation technologies. At present, evolving information, communications, and sensor technologies and innovative transit operations control strategies are becoming critical elements of a viable, competitive public transit system. As innovative technological solutions are integrated with transit services, it is useful to have a tool for testing and evaluating the impacts that these strategies may have on transit performance and on other parts of a transportation network.

Such a tool should be able to realistically represent the behaviors of buses traveling along their routes. The tool should also accurately simulate the temporal and spatial variation in passenger demand at bus stops. Therefore, the aim of the research is to model bus transit services at the system, route segment and bus stop levels in order to fully capture bus transit operations dynamics and to lay the groundwork for the testing of APTS solutions.

MITSIMLab is the simulation laboratory used for the implementation of the bus operations modeling described in this thesis. MITSIMLab is a microscopic traffic

simulation laboratory developed for ITS design and evaluation. The goal of this research is to extend MITSIMLab's functionality to include bus operations and its evaluation framework to support APTS. MITSIMLab is made up of three major components: the traffic flow simulator (MITSIM), the traffic management simulator (TMS) and the graphical user interface and measure of effectiveness module (GUI/MOE). The modeling effort required in order to add the capacity for APTS simulation to MITSIMLab called for improvements to these MITSIMLab modules.

The MITSIM module simulates the movements and decision-making behaviors of individual vehicles traveling between their origin and destination. MITSIM was given a better, more sophisticated representation of bus transit supply and demand with the purpose of better simulating the interactions between vehicles in a multi-modal traffic environment. Surveillance features, too, were modified in MITSIM to simulate the detection of buses by short-range radio communication with traffic signal controllers and the generation of vehicle location information under various automated vehicle location (AVL) schemes. In order to better understand the impacts of various APTS strategies, the performance of buses along their routes, and the passengers' experiences during a simulation, it was necessary to enhance the GUI/MOE module of MITSIMLab to produce output relevant to bus transit performance.

A case study was conducted in order to demonstrate the functionality added to the MITSIM and GUI/MOE modules. The objective of this case study, in addition to illustrating the value of the research presented in this thesis, is to evaluate conditional bus signal priority on an urban arterial network in Stockholm, Sweden. The signal controller logic in the TMS module was used to simulate conditional signal priority. MITSIMLab's TMS module simulates the logic that governs the traffic control system performance (e.g. traffic signals, route guidance, and traveler information). The adaptation of TMS' signal controller logic to allow conditional bus signal priority demonstrates the primary objective of this research, the application of a bus transit operations-enhanced MITSIMLab to APTS testing and evaluation.

1.2 Thesis Outline

The remainder of this thesis is outlined as follows: Chapter 2 is a review of existing and emerging APTS technologies. Chapter 3 provides a discussion of the various features that would be required of a bus simulation model in order to simulate these APTS solutions.

Chapter 4 introduces MITSIMLab and the details of those modules in MITSIMLab that are pertinent to the bus transit modeling effort. In Chapter 5, the implementation of the various bus transit models and of the related improvements to MITSIMLab's pre-existing models is presented. Chapter 6 describes the case study conducted to demonstrate the use of the models to evaluate conditional bus signal priority on a network in Stockholm, Sweden. Finally, Chapter 7 summarizes the conclusions and findings drawn from the research and recommends topics for future research.

Chapter 2

Review of APTS Technologies

Chapter 1 gives an introduction to the motivation for, and the objective of, this thesis, to develop a microscopic traffic model's ability to simulate bus operations in a way that supports the simulation and evaluation of APTS. Before initiating a discussion of bus operations modeling techniques, however, this chapter provides a general review of existing and emerging APTS. Having established an understanding of how various APTS operate and interface with various aspects of bus operations, Chapter 3 opens the topic of how to represent bus operations in a traffic simulator in order to simulate APTS at the operational level.

2.1   Background

Advanced Public Transportation Systems (APTS) are those Intelligent Transportation Systems (ITS) technologies applied to public transit in order to improve operational efficiency, cost savings, safety, quality of service or other transit measure of performance. Some APTS applications offer potential for improving service by providing greater leverage to service providers for managing and controlling bus transit operations. Other APTS applications provide benefits in terms of speed, security and convenience directly to the customer. These and other APTS have the potential to significantly change the way transit services are provided to the customer and the way customers use the service. Increasingly popular technologies such as Automated Vehicle

Location (AVL) systems, Automatic Passenger Counters (APC), and Electronic Fare Payment will have a wide variety of impacts on bus transit operations.

The history of APTS is a short one. Table 2-1 illustrates the evolution of on-board transit vehicle technologies such as automated passenger counters and automated vehicle location systems (AVL). APTS was born out of the increasing popularity of ITS.

Table 2-1: The evolution of on-board technologies in recent decades (Schiavone, 1999)

	1970's	1980's	1990's
Drivetrain	- Alternator - Voltage Regulator	- Engine Controls - Transmission Controls	- Antilock Brakes - Traction Control
Body/Chassis	- Farebox	- Magnetic Ticket Readers - Door Controls	- Smart Cards - Multiplex Wiring System - Brushless Motors - Hubodometer
Communications	- Destination Sign - First Sign Post - AVL demo	- First AVL to transmit performance data	- Camera Security System - Auto Stop Annunciation - GPS AVL - Infrared Passenger Counter

The first examples of APTS in practice date back to the late '60s and early '70s with the introduction in the United States of Automated Vehicle Monitoring (AVM) systems. The majority of these vehicle location technologies were signpost-based systems, which require the installation of stationary signposts along bus routes. These signposts are equipped with electronic transmitters that emit unique identification codes. When a bus passes the signpost, an in-vehicle locating unit and receiver receive the signpost's identification code and record the time and date, the difference between the current odometer reading and the last (recorded at the previous signpost), and the vehicle's identification code. Either periodically or when prompted by the transit operations control center (TOC), the bus sends the information to the TOC via radio or other medium.

The first implementations of APTS, like the signpost-based vehicle location systems, were expensive to install, operate and maintain. Since then, new technologies,

such as geographic positioning systems (GPS), have emerged and declined in cost. Other evolving technologies that have been identified for application to APTS include information technology, sensor technology, communications technology, and geographic information systems. Since these new technologies have begun to increase in availability and affordability, the trend in APTS deployment is increasing. Table 2-2 shows the increasing number of APTS at various stages of development, as determined by a survey of various transit agencies, since 1995.

Table 2-2: The increasing adoption of APTS by transit agencies

APTS Elements	1999 STATUS			% increase from 1995
	Operational	Implementation	Planning	
AVL	61	25	75	259
Advanced Communications	140	20	61	202
Automated Passenger Counts	24	6	34	118
Vehicle Component Monitoring	13	7	24	180
Automated Transit Information	89	25	50	108
Automated Transit Operations Software	40	14	42	72
Traffic Signal Priority	16	7	33	N/A

The most popular systems, as evidenced by Table 2-2, is AVL, which, as will be shown later in this chapter and in Chapter 3, is an important component of a variety of other APTS applications. In most cases, the number of systems in the planning and implementation stages is a considerable percentage of the total number of operational systems at the time of the survey. Similarly, Figure 2-1 illustrates the rising adoption of APTS in transit agencies in North America from the same survey (FTA, 1996). Figure 2-1 shows a sharp increase in the later years. If the trend in increasing acceptance and application of APTS continues as is expected, a simulation tool for the evaluation and design of APTS could prove to be invaluable.

Trends in AVL Implementation

(Source: 1991-1996 - *State of the Art Reports*; 1997, 1999 *Deployment* Reports)
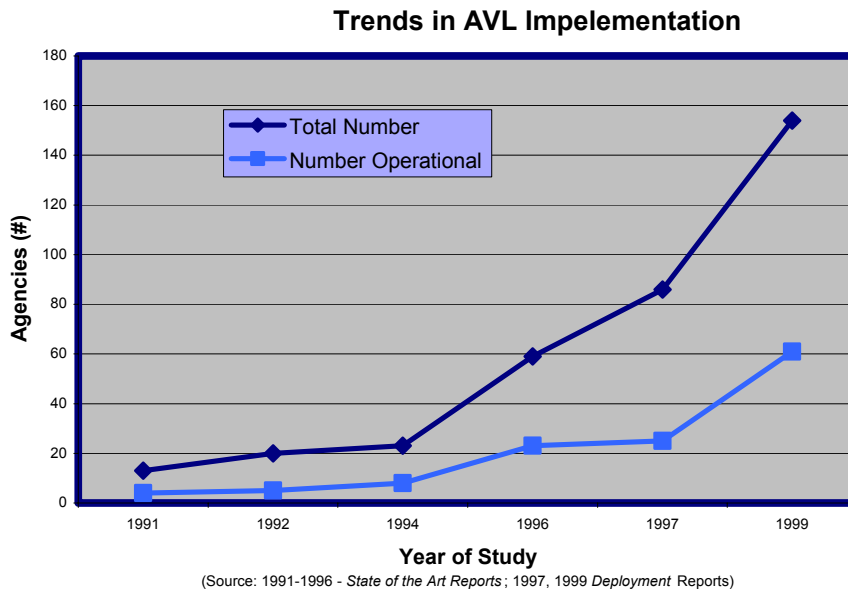
Figure 2-1: The growing number of transit agencies using APTS

The Federal Transit Administration (FTA) groups existing and emerging APTS into 4 categories (FTA, 2000):

1. Fleet Management
2. Traveler Information
3. Electronic Fare Payment
4. Transportation Demand Management

Fleet management applications refer to "vehicle-based" technologies that may be used to improve vehicle planning, scheduling and operations. Some fleet management technologies include geographic information systems (GIS), automated vehicle location (AVL) and bus signal priority. Traveler information technologies are designed to provide pre-trip and en-route information to travelers to allow them to make informed trip-making decisions. Electronic fare payment includes the range of technologies designed to reduce costs associated with fare collection and to improve customer convenience. Finally, transportation demand management, such as dynamic ridesharing and high occupancy vehicle (HOV) lane monitoring, refers to systems aimed at better management of the existing transportation network infrastructure.

In order to be able to simulate the use of APTS, it is important to understand the details of their operation, the inputs they require and the outputs they generate. More importantly, it is necessary to understand the features of bus transit systems with which the technologies interact, so that the bus transit operations models are developed in such a way that supports the simulation of the technology. Sections 2.2-2.5 address the operational issues associated with each of the aforementioned APTS application areas.

2.2 Fleet Management

Fleet management strategies focus on improving the planning, scheduling and operations of a fleet of vehicles. Some motivations for fleet management technologies include improved service reliability, improved safety, improved operating efficiency (e.g. reduced non-revenue time, increased productivity), and faster service disruption recovery. Figure 2-2 shows the increasing deployment of AVL and transit operations software such as Computer-Aided Dispatch (CAD) from a survey of 78 metropolitan areas (FHWA, 2001).
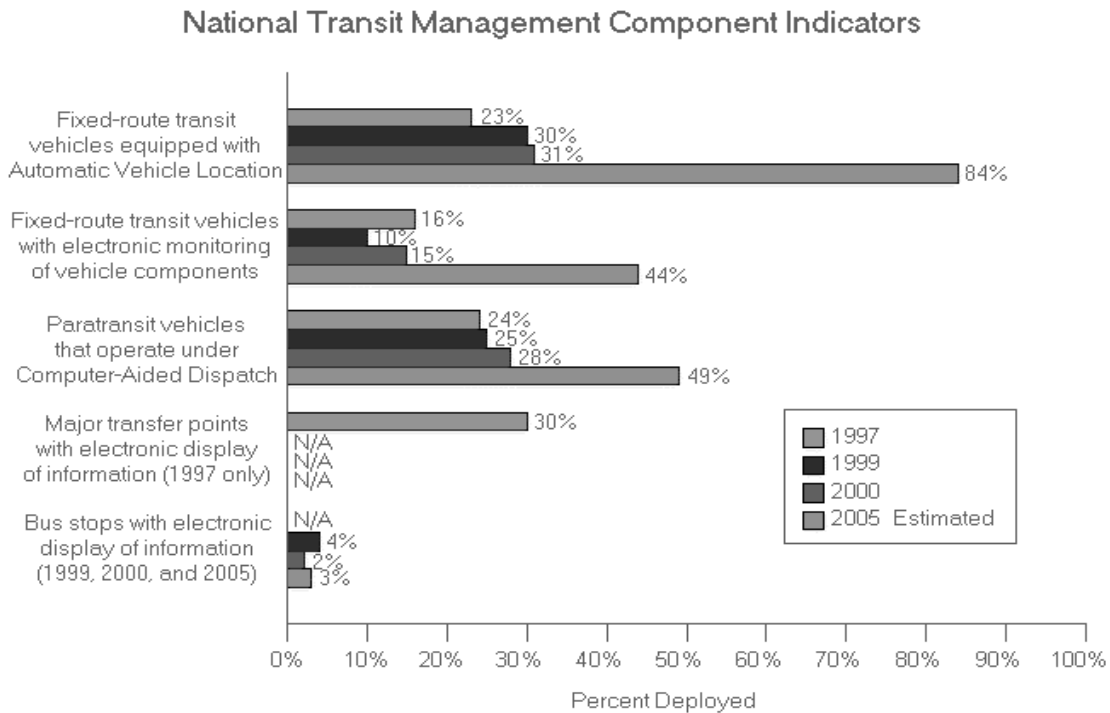
Figure 2-2: Trends in increasing deployment of APTS (source: FHWA, 2001)

In general, fleet management technologies are those that collect and make available valuable vehicle performance data (e.g. vehicle location) and those that use that data for real-time control or for planning and scheduling. The FTA focuses on 6 different fleet management systems (FTA, 2000):

- Communications Systems
- Geographic Information Systems
- Automated Vehicle Location Systems
- Automatic Passenger Counters
- Transit Operations Software
- Traffic Signal Priority

Each of the technologies listed above, and the operating principles by which they function, is discussed below.

2.2.1 Communications Systems

Communications systems are the technologies that allow the sharing of information between the vehicle and the transit operations control center, between the vehicle and field-installed technologies, such as traffic signal controllers for bus signal priority or access facilities for HOV or dedicated bus lanes, and between the service provider and the customer. Communications systems enable vehicles to interact with traffic control devices that require information about fleet performance as input. Communications systems also make it possible for the TOC to monitor vehicle performance and to exercise control over vehicle movement and behavior.

There are a wide variety of systems for sending voice and data (e.g. analog, digital, cellular digital packet data) between transmitter and receiver, including two-way radio and short-range communications. Furthermore, the type and quantity of data relayed between vehicles and field-deployed devices and between vehicles and the TOC vary from application to application. Some basic properties of communications systems, however, are common to all applications.

Some of the more important architectural characteristics of the communications system include the ownership, storage and distribution of the data in question.

Ownership refers to with which entity in the system (e.g. vehicle, field-installed device, TOC) the data resides or originates. For example, a bus "knows" certain constant attributes about itself (e.g. identification code) as well as dynamic information (e.g. location) collected by on-board equipment. Storage relates to the amount of information or length of time during which information is kept before it is purged or transmitted and depends on the technology.

The third, and key, dimension of the communications system is the distribution pattern, which defines the relationships, both spatial and logical, between the different information-sharing components of the system. For example, a vehicle may only be able to communicate with field-installed devices when it is within range of the communications equipment. Furthermore, the data may be transmitted at specified intervals or when queried by another device. For example, in AVL applications, vehicle location data are most commonly transmitted to the TOC via polling or exception reporting (FHWA, 2000). With polling, a computer at the TOC continuously or periodically cycles through all operating vehicles in the fleet, requesting each vehicle's location. With exception reporting, the vehicle sends its location data to the TOC only when it reaches specified locations or when the vehicle is running sufficiently behind schedule.

2.2.2 Geographic Information Systems

Geographic Information Systems (GIS) are database management systems that assemble, store, manipulate and display geographically referenced data. GIS data is collected using the Global Positioning System, a system of satellites that transmit radio signals that may be captured by a GPS receiver and used to calculate the user's geographic position. Thus, GIS can be used to trace the movements of vehicles in time and space and to study the relationships between demographic data and route structure and bus stop location. GIS position data may be used to serve a variety of transit-related purposes, including route planning, automated vehicle location and bus dispatching.

Many GIS applications in transit have to do with vehicle location systems. GPS accuracy can be within 10 to 20 meters. However, many factors can affect the reliability of a GPS measurement, such as signal coverage (e.g. signal blockage due to tunnels or

tall buildings), noise effects and signal integrity. The receivers translate the satellite signals into position, velocity and time measurements. According to the communications system design, this and other data might then be transmitted to an TOC.

2.2.3 Automated Vehicle Location Systems

Automated vehicle location systems combine vehicle location and communications systems in order to automatically track the locations of a fleet of vehicles. AVL is an integral component of automated vehicle monitoring and control (AVM/C), emergency vehicle location, fleet management, traffic signal priority, and many more transit applications. AVL can be used to monitor schedule adherence, estimate arrival times, and communicate location data to an TOC or to field-installed devices that require real-time vehicle location data.

The communications system controls the flow of information between the vehicle's on-board computer, the TOC central computer and the vehicle location devices (e.g. satellites, signposts). The vehicle's on-board computer receives and processes signals incoming from the vehicle location devices. The TOC computer then manages the data incoming from each vehicle in the fleet. In many AVL implementations in the U.S., the TOC receives location data from the fleet every 1.5 to 2 minutes (Okunieff, 1997). Often, a particular time interval for reporting is allocated to each vehicle in the fleet. With incoming real-time information about the locations of transit vehicles in the network, dispatchers at the TOC can make meaningful deductions about the performance of each route and employ other APTS solutions, such as Computer-Aided Dispatching (CAD) (described in Section 2.2.5) to respond more quickly to emergencies and to apply strategies for maintaining and restoring service. The incoming vehicle location information can also be stored and used as input to the route and schedule planning process.

2.2.4 Automatic Passenger Counters

Automatic passenger counters (APC) are systems that count passengers as they board and alight the vehicle at a stop. APCs can reduce the cost of manually collecting ridership data. APCs may be used with AVL systems in order to record the spatial

distribution of passenger demand along a vehicle's route. APC technologies include treadle mats, which recognize passengers when they step on the mat, infrared beams, which recognize passengers when the beam is broken, and computer imaging, which is still in the development stage. Real-time information regarding passenger loads on a vehicle may also be useful inputs to real-time transit operations control. However, the majority of uses of APC data to date are of a planning nature. Table 2-3 lists the most common uses of APC data from a survey of 33 transit agencies conducted to determine the state of the practice of APC (Boyle, 1998).

Table 2-3: Common uses of APC data.

Uses	Number of Systems
Assess changes in ridership	32
Add or delete trips	31
Revise (change, continue or add) routes	31
Calculate performance measures	30
Adjust running times	27
Determine locations for bus shelters	26
Other	10

The way that passenger counts are recorded and stored on the vehicle varies according to the APC technology. Typically, the APC records the stop location, the time and date of arrival at the stop, the time the doors open and close, the number of passengers boarding and the number of passengers alighting (FTA, 2000). This data is referenced to a particular trip and is stored on the vehicle for some period of time until it is either retrieved by a computer at the depot when the vehicle returns or by the TOC in real-time. This storage and distribution of passenger count data depends on the communications system employed by the service provider.

2.2.5 Transit Operations Software

Computer software is another fleet management tool used to improve planning efforts and real-time operations control. There are available transit operations software solutions for route planning, crew scheduling and other offline applications. Transit operations software for real-time applications also exists. The most common real-time transit operations software is Computer-Aided Dispatching (CAD), which is usually

combined with AVL systems. The AVL system provides real-time vehicle location data, which is then used by the CAD application to devise a strategic dispatch control response.

CAD software has a variety of potentially useful applications. APTS: State of the Art Update 2000 identifies 4 applications for CAD software: Transfer Connection Protection (TCP), expert systems for service restoration, itinerary planning systems and service planning applications. TCP software compares real-time vehicle performance to the schedule and determines whether transfers to vehicles on connecting routes will be achieved. Expert systems for service restoration use dispatcher experience, operating rules and procedures, historical service disruption response data and real-time AVL data to make informed operations control decisions. Itinerary planning systems help passengers decide the best route(s) between a given origin and destination. Finally, service planning applications analyze and develop service reliability measures to aid planning and scheduling solutions for improving service.

The usefulness of transit operations software for real-time transit operations control depends on how dispatchers use the information provided by the AVL/CAD system. The degree of automation of AVL/CAD systems determines the level to which the system relies on dispatcher discretion. For example, New York City Transit (NYCT) is planning to implement a computer-aided support management (CASM) system designed to help dispatchers to improve service regularity (FTA, 2000). CASM, given schedule information, real-time AVL data, and other inputs, will generate a number of candidate control strategies in response to degradations in headway maintenance and schedule adherence. These strategies, which might include dispatching a new bus to the route, instructions to skip stops and other control measures, are then left to the dispatcher to make the final decision.

2.2.6 Traffic Signal Priority

Traffic signal priority involves the modification of a signal's regular timing plan, in real-time or in advance, to give preference to transit vehicles. Traffic signal priority is designed to reduce transit vehicle delays at signalized intersections. Reduced delay to transit vehicles can serve to reduce overall travel time, aid schedule adherence and

headway maintenance, and increase person throughput at the intersection. Traffic signal priority generally relies at least on some communications system to allow approaching transit vehicles to alert the traffic signal controller of the vehicle's approach or to allow the signal controller to detect the vehicle's presence.

Transit signal priority strategies are varied: they can be passive or active and unconditional, conditional or adaptive. Passive priority requires no communication between vehicle and controller and involves the development of a fixed signal timing plan that reduces delay on the transit vehicle's approach. Passive priority can be achieved by allotting more green time to the transit vehicle's approach, reducing the cycle time to reduce the delay until the next green phase, coordinating signals to improve progression along a corridor, and other methods. Active priority, on the other hand, does require technologies that permit communication between the vehicle and the signal controller and that enable the controller to calculate the appropriate response. Active signal priority dynamically adjusts the signal timing when the transit vehicle is detected. Active priority may be afforded by extending the green interval in the current phase, by terminating the current phase to start an early green interval for the transit vehicle's approach, or by inserting an extra green phase on the vehicle's approach.

Active traffic signal priority can be unconditional, conditional or adaptive. Unconditional strategies give priority to every equipped (e.g. with on-board communications systems) transit vehicle that approaches the intersection regardless of the vehicle's schedule or the impacts on the conflicting approaches. Conditional priority grants priority to approaching transit vehicles only if the approaching vehicle meets some predetermined condition(s). The condition for priority might depend on the vehicle's location with respect to the schedule (i.e. whether the vehicle is ahead of or behind schedule), passenger load, headway or other measurement. Thus, communications and controller technologies that support conditional signal priority must be able to transmit and manipulate various pieces of data for evaluating priority eligibility depending on the application. Adaptive traffic signal control involves the detection of traffic volumes on all approaches, the calculation of an optimal timing plan and the real-time adjustment of the timing plan. Adaptive control can incorporate conditional or unconditional transit priority by adding weight to the transit vehicle's approach accordingly.

2.3   Traveler Information

Traveler information systems in transit applications refer to the use of technology to provide travel information to passengers in order to assist their trip-making or route choice decisions either prior to departure or en route. The information provided may vary from static route, schedule and fare information to real-time vehicle location and/or estimated arrival time. Real-time information can be offered to travelers when the traveler information system is used in conjunction with AVL systems. Furthermore, traveler information might be disseminated through the use of transit operations software such as itinerary planning systems. Traveler information is generally expected to improve the quality of transit service by improving the passenger experience. Traveler information may grant passengers a better sense of control over their trip-making decisions and/or enable them to take action to minimize their waiting times at stops, plan their transfer connections and thus reduce their overall travel time. Figure 2-2 also shows that deployment of traveler information systems at major transfer points and bus stops in 78 metropolitan areas has been very limited, indicating that transit traveler information systems have yet to capture widespread acceptance (FHWA, 2001).

Information may be provided prior to departure (e.g. by phone, internet), at the terminal or stop or in the transit vehicle. The FTA divides traveler information systems into three categories (FTA, 2000):

- Pre-trip transit and multimodal traveler information systems
- In-terminal/wayside transit information systems
- In-vehicle transit information systems

Various factors affect passenger trip-making decisions, including service characteristics such as frequency and coverage. Different types of information (e.g. static or real-time) and different methods for accessing that information (e.g. via the internet at home or in-vehicle announcements) will likely have different effects on how traveler travelers use different types of service (e.g. high frequency and low frequency). Thus, there are a wide variety of traveler information systems that are designed to influence specific traveler behaviors and decisions. Below, each of the categories of traveler information systems listed above is discussed.

2.3.1 Pre-Trip Transit and Multimodal Traveler Information Systems

Pre-trip traveler information systems imparts to the user information relevant to the choices that are made prior to departure. These pre-trip decisions include choice of mode, route and departure time, thus enabling travelers to choose a course of action that best serves their trip purpose. A review of the state of the art of APTS reveals four types of pre-trip traveler information: General Service Information, Itinerary Planning, Real-Time Information and Multimodal Traveler Information (FTA, 2000).

General Service Information systems offer static information, such as route, schedule and fare information. This information can be accessed by phone or by consulting maps and timetables that are posted on vehicles, at stops, or on the Internet. Itinerary planning systems allow travelers to consider a variety of factors such as travel time, walking distance, cost, and number of transfers. With these criteria in mind, the traveler may choose from among the alternative trip plans that connect their origin to their destination. Real-time Information makes use of AVL data to provide current vehicle performance information to users. Performance data might be used to provide either the current locations of transit vehicles or the estimated arrival times of vehicles at stops along the route.

The fourth type of pre-trip information is Multimodal Traveler Information, which provides real-time and/or static traffic and transit information. Multimodal information requires ITS technologies that measure and estimate the current state of the traffic network as well as transit-specific technologies that provide transit information. Generally, the aim of Multimodal Traveler Information is to advertise the benefits (e.g. less travel time) of traveling by transit and thus to attract transit riders. Figure 2-3 shows the increasing deployment of regional multimodal traveler information (RMTI) systems that provide information about more than one mode (FHWA, 2001).

National Regional Multimodal Traveler Information Component Indicators
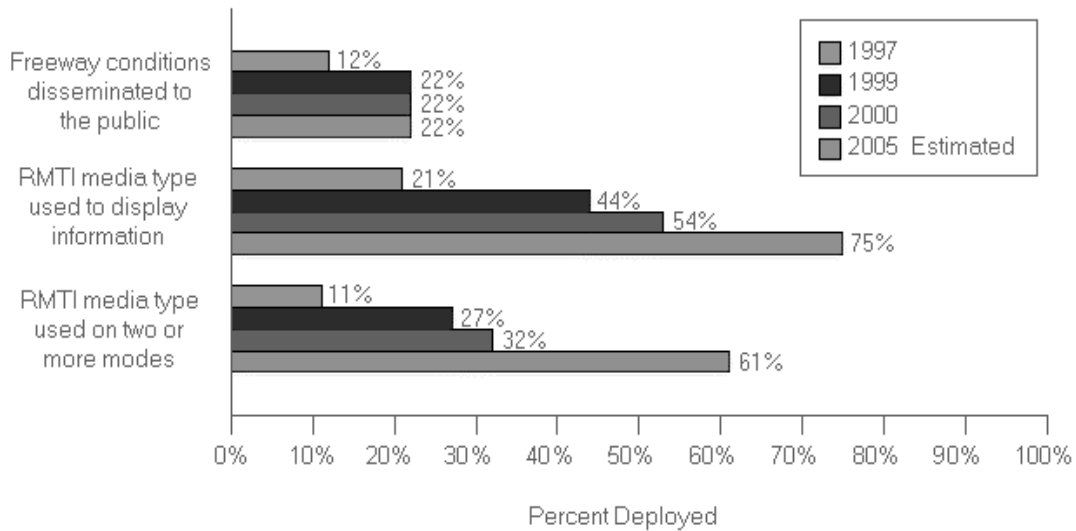
Figure 2-3: Increasing deployment of multimodal traveler information systems
(source: FHWA, 2001)

Traveler response to pre-trip information has been hypothesized and modeled in the literature. It is important to distinguish between low frequency, regular services (e.g. suburban and off-peak urban routes) and high frequency, irregular services (e.g. urban routes) when considering transit passenger route choice. It is generally assumed that, for low frequency services, passengers choose both the stop and the trip (i.e. scheduled departure time) before the trip begins. With high frequency services, passengers are assumed to choose only the stop prior to starting the trip. The choice of various stops on routes that serve the passenger's destination can be modeled according to random utility theory, where each candidate stop in the choice set has some utility value that is a function of the stop's attributes. Therefore, various types of pre-trip information (e.g. schedules, estimated arrival times) might contribute to the perceived utility of a stop and have a significant impact on traveler pre-trip stop choice. For high frequency services, it is assumed that passengers develop, prior to departure, a choice set of candidate routes that serve the origin stop. Choice of the actual trip from the set of alternative routes is assumed to take place en-route. However, pre-trip static and/or real-time information can play an important role in the traveler's consideration of possible routes.

2.3.2 In-Terminal/Wayside Transit Information Systems

Traveler information systems that provide information to travelers while they wait at stops are designed to provide waiting customers with current information regarding delays, estimated arrival times and other real-time vehicle performance data. Real-time information at terminals relies on AVL systems that track vehicle locations along their routes and communicate that location data to a central computer (e.g. TOC), which then displays the information at the stop. Real-time information might be relayed to waiting passengers via video monitors or variable message signs. Passengers at the stop may use the information to make en-route decisions such as which approaching vehicle to board if multiple routes serve the passenger's destination. For other passengers, the information may simply offer assurance regarding their expectations of the service, thus improving the passenger's overall experience.

The FTA identifies other technologies that may be adapted to in-terminal/wayside traveler information systems to convey real-time information to the users (FTA, 2000). These include cellular phones, alphanumeric pagers and handheld computers with Internet access. Through these technologies, a central computer, which receives and processes incoming AVL data, may distribute information directly to the passenger. Thus, these technologies, combined with a traveler information system and AVL system, may provide pre-trip and en-route information to transit riders.

The information provided at transit stops may or may not influence passenger route choice. For low frequency, regular services, it is assumed that travelers have already chosen a stop and a trip prior to departure. Therefore, in the case of low-frequency services, in-terminal/wayside information may be used to ease customer frustration and impatience during delays. However, in-terminal/wayside information can influence the passenger's en-route decision-making behavior in the case of high frequency services. For example, if more than one route serves the origin stop, the traveler may choose from among a set of approaching vehicles that serve the destination. According to random utility theory, each approaching candidate trip has some utility associated with it, which might be a function of traveler information. Nuzzolo et al. (2001) expressed the utility of an approaching trip in the choice set as a function of:

- Waiting time (the difference between the estimated arrival time of a trip and the estimated arrival time of the base trip), provided by the information system
- In-vehicle travel time
- Transfer time to the connecting trip
- Number of transfers
- On-board comfort = (load/capacity)$^\delta$ (i.e. level of crowding on-board between the origin and destination stops)
- Time already spent at the stop

The model was calibrated with SP data collected from transit riders in Salerno, Italy. The waiting time parameter, equal to -0.85, was statistically significant (t-statistic = -4.44), almost two times that of the in-vehicle travel time (-0.46), greater than the transfer time (-0.70), and more than two times that of the number of transfers (-0.39). Therefore, transit passengers at least have an expressed interest in in-terminal/wayside information and would likely use that information in their en-route decision-making.

2.3.3 In-Vehicle Transit Information Systems

In-vehicle information systems use public address systems, either automated or performed by the operator, variable message signs and other on-board systems to communicate information to the passengers. In-vehicle information might include the name of the next stop, transfer opportunities at the stop, points of interest near the stop, and other information relating to upcoming stops. There is less opportunity to influence a passenger's route choice decision-making on a transit vehicle, since the passenger has already chosen a stop at which to board, the vehicle (or trip) and, presumably, a destination. However, some real-time information, such as the whereabouts of connecting vehicles at downstream stops might be conveyed using in-vehicle information systems. The user, then, may update the destination stop choice or begin planning the next leg of the trip based on the prevailing connection prospects. Like the other information systems, the provision of real-time information regarding connecting routes depends on the AVL system in place.

In-vehicle traveler information systems, however, may influence the behavior of passengers aboard the bus. For example, the announcement of a stop may prompt

passengers expecting to alight at the stop, especially those not familiar with the system, to begin the approach to the exit doors. If this is the case, the time required to discharge all passengers at the stop may be reduced with the provision of in-vehicle information. Reduced alighting time may lead to a reduction in total dwell time at the stop, and thus affect the progression of the vehicle from stop to stop along its route.

2.4   Electronic Fare Payment

Electronic fare payment technologies forego cash and token payment with the aim of reducing the operating costs of fare collection systems, increasing safety and security on the vehicle, improving data collection and increasing revenue by adding customer convenience. Figure 2-4 demonstrates the increasing interest in electronic fare payment systems from a survey of 78 metropolitan areas (TRACKINGITS).
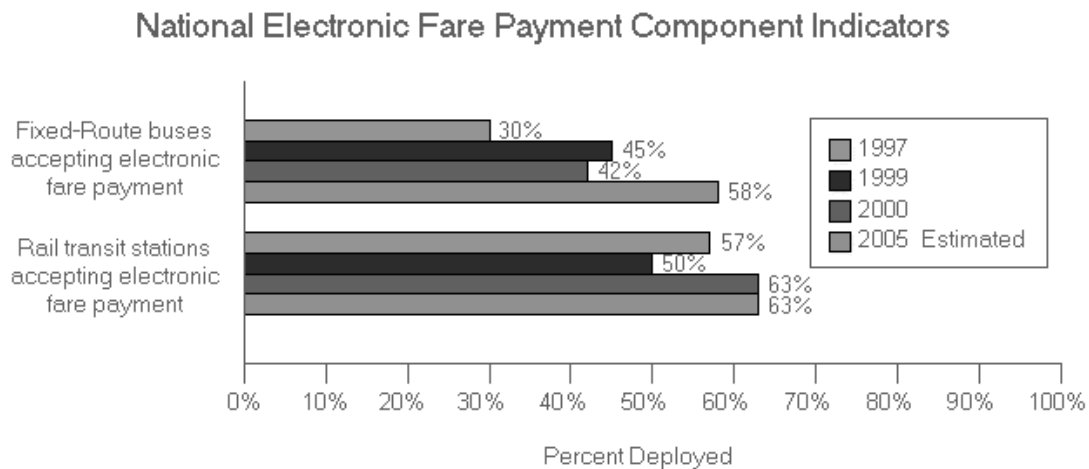
Figure 2-4: Increasing deployment of electronic fare payment systems
(source: FHWA, 2001)

There are several available electronic fare payment technologies, including magnetic stripe cards and smart cards. Added customer convenience arises from the ability to use one card to pay for all services, thus eliminating the need for cash, tokens, transfer slips and other traditional means of fare payment. Some systems, such as the more advanced smart card systems, may track the remaining balance on a card so that a lost or stolen card may be reissued and redeemed and may also offer automatic credit card or bank

account billing options. The potential advantages of electronic fare payment are many and far reaching. For instance, other benefits include the ease of implementation of more sophisticated fare pricing strategies.

Electronic fare payment technologies can have significant impacts on transit operations. The most obvious of the potential impacts on operations occurs at the bus stop, where passengers board and alight from the vehicle. Depending on the type of electronic fare payment technology, considerable gains can be made in terms of reducing dwell times at stops by increasing the speed with which waiting passengers pay and board the vehicle. Contact card technologies, where the card is physically swiped through a card reader, and contactless card technologies, where the card and card reader communicate without physical contact but rather via an electromagnetic signal, will affect passenger boarding rates differently. Boarding rates will increase to a greater extent with contactless card technologies because the passenger will neither have to remove the card from a pocket, wallet or purse nor manually run the card through a reader. The gains in boarding speed, however, will diminish as crowding aboard the vehicle limits the rate at which passengers may physically maneuver past standees into the bus.

2.5 Transportation Demand Management

Transportation demand management is the application of technology to alter the usage patterns of the transportation network, with an emphasis on encouraging users to travel by transit. There is a broad range of technologies designed to better coordinate various transit services, to provide forums for organized carpooling and to better manage the movement of transit vehicles through improved transportation system monitoring. Each of these, and other, approaches to managing transportation demand seek to provide benefits to travelers, either in terms of convenience or in terms of more tangible benefits like reduced travel time, in order to reduce the number of single-occupant vehicles in congested, polluted transportation networks.

UPDATE2000 highlights three transportation demand management strategies that exist in practice or are currently in the planning stage in the United States:

- Dynamic Ridesharing

- Automated Service Coordination

- Transportation Management Centers

Each of these strategies aims to entice travelers to use alternative modes of transport (i.e. versus private automobile) or to rideshare in different ways. Transportation demand management applications rely on various ITS technologies and may or may not affect bus transit operations. Below is a discussion of each of the three strategies listed above.

2.5.1 Dynamic Ridesharing

Dynamic ridesharing systems are designed to promote community ridesharing by providing a convenient network for bringing together drivers and passengers with common trip plans. The motivation for dynamic ridesharing is the reduction of single-occupant vehicle trips. Participants (i.e. drivers and passengers) who wish to carpool may submit an entry to a computerized system, either via telephone or via the Internet, giving the details of their desired trip, such as departure time, origin and destination. The dynamic ridesharing system software then searches its store of previous entries to find one or more matches. Drivers may wish to carpool in order to share the cost of the trip or in order to use HOV lanes to reduce their travel time. Passengers wishing to carpool may not have access to their own vehicle, may be seeking alternative modes of transport or may also be seeking to reduce travel costs and travel time.

Dynamic ridesharing systems, either managed by a transportation agency or by members of the community, provide an organized forum for carpoolers to find and meet other carpoolers with like trip origins, destinations and departure times. Such a system might potentially reduce the vehicle demand for the network and introduce significant gains in congestion mitigation. Generally, dynamic ridesharing does not require any other technology than a website or telephone-based access system and the software that manages the user information.

2.5.2 Automated Service Coordination

Automated service coordination is designed to improve the presentation and availability of information regarding public transit services offered by more than one provider in a given region. Traditionally, services offered by various transit agencies are independent, non-complimentary and uncoordinated. In these traditional systems, the customer must gather route, schedule and fare information from more than one source and suffer the inconvenience associated with transferring between two separate systems that do not communicate. Automated service coordination pools together the resources of the different agencies and uses available ITS technologies to make it more convenient and attractive for travelers to use some or all parts of the regional transit system.

Various approaches might be adopted to apply ITS technologies to service coordination. For instance, automated fare payment systems may allow customers to transfer from one system to another without paying two fares. AVL systems might be applied across all parts of the system and monitored by one coordinating body in order to advise bus operators and passengers with respect to transfer connections, delays and other useful information. By coordinating transit services among various providers, a regional transit system may be made to appear to the customer as one seamless system and thus have a considerable impact on the way passengers use and travel about the system.

2.5.3 Transportation Management Center

A third example of travel demand management, which is being adopted by cities across the United States, is the transportation management center (TMC). The TMC is a central control center that monitors some or all aspects of the transportation network (e.g. traffic and transit), manages the incoming information from field-installed sensors, detection devices and communications-equipped vehicles and initiates congestion mitigation, service restoration and other strategic responses to degradations in network performance. For example, a TMC might observe traffic sensor measurements in real-time to determine the state of the network and thereby develop and disseminate route guidance information to drivers via variable message signs or via satellite communications. Likewise, the TMC may monitor transit vehicle locations and issue instructions to operators for restoring service in the case of disruption or for avoiding

incidents detected along the route. TMC operations also allow for more rapid incident detection and emergency response.

The transit management center is where all parts of real-time, operational APTS applications come together, where information made available in real-time by transit ITS technologies such as AVL may be used to make informed, dynamic and adaptive decisions to aid the progression of transit vehicles along their routes and improve system performance. Passenger demand affects transit vehicle progression, and, in turn, system managers at the TMC make decisions that affect how the transit vehicles operate in service of those passengers. Therefore, at the TMC there is great potential for supply-demand interaction, and an important opportunity for transit system managers to make a profound impact on bus transit operations. The following chapter describes various transit operations models that may enable a simulation laboratory to represent the behaviors of and interactions between the TMC, the transit vehicles, the passengers and the APTS technologies under evaluation.

Chapter 3

Model Requirements for APTS Simulation

Chapter 2 provides a general review of the state of the art of APTS and raises a number of issues regarding the simulation of APTS in a microscopic traffic simulation laboratory. This chapter addresses those issues and identifies the features that a simulator must have in order to simulate APTS. Chapter 4 follows with a discussion of a framework for implementing the requirements identified in this chapter into MITSIMLab, an existing simulator.

3.1 Identification of Requirements

In order to simulate APTS applications in bus transit, it is necessary to represent bus transit operations at a level of detail that supports the operational characteristics of the technology or system of interest. For example, AVL/CAD systems that monitor bus performance and determine holding and dispatching solutions to schedule deviations cannot be simulated in a model that does not represent the bus transit schedule. The purpose of this chapter, then, is to summarize the requirements for a microscopic traffic and transit simulation model to be able to simulate APTS.

At the core of a good microscopic traffic simulator are sophisticated driver and traveler behavioral models that capture the complex interactions between vehicles and between vehicles and traffic control and information systems. Similarly, APTS simulation should be based on a detailed, veritable representation of bus transit

operations. For the purposes of this thesis, bus transit operations refer to the movements and behaviors carried out by individual buses in service of their assigned routes. Bus transit operations are subject to a number of incidental and controlling forces, including service schedule design, passenger demand, and dispatcher control and intervention. In general, a bus transit service provider abides routinely by an adopted set of service standards and policies that govern bus operations. Bus transit passengers, whose behaviors are considerably more random, also strongly influence the way buses operate in performance of their assigned pieces of work. At the same time, a dispatcher at an operations control center (TOC) may monitor each bus' performance and give instructions regarding when and how to proceed along a route.

These various forces are not independent of one another. For instance, buses travel along their routes according to a schedule, passenger crowding may slow bus progression, and consequently the bus may deviate from the schedule. In turn, with the aid of APTS, dispatchers may intervene to give the bus operator instructions for recovery. Thus, bus transit operations are a function of the interactions between the systematic (e.g. bus schedule) and random (e.g. passenger demand) elements of the bus transit system that are a necessary consequence of the provision and the patronage of the service. In order to simulate the interaction between these elements of bus transit systems, and to derive meaningful conclusions from such a simulation, the following are identified as fundamental requirements of a microscopic simulator:

1. Transit System Representation:

   Transit system representation refers broadly to the system level components of bus transit operations that are generally under the control of the transit service provider. The transit system representation includes the transit network, schedules and fleet assignments.

2. Transit Vehicle Movement and Interactions:

   Transit vehicle movement and interactions includes the microscopic vehicle operator-controlled movements of individual vehicles along their routes, such as acceleration, lane-changing, and door opening and closing, as well as the behaviors of non-transit vehicles in the presence of buses.

3. Demand Representation:

   Demand representation refers to the passengers, or customers, and their behaviors with regard to use of the system, including en route and pre-trip mode and route choice, as well as behavior at bus stops, such as boarding, alighting and crowding.

4. APTS Representation:

   APTS representation involves the representation of surveillance and monitoring systems that generate and distribute real-time information, the application of that data to real-time control strategies, and the provision of information to travelers.

5. Measures of Effectiveness

   Measures of effectiveness include the indicators, levels of service and other measures of performance that are used to evaluate the performance of an APTS strategy. The reliability of the measures of effectiveness generated by a simulation is dependent upon the strength of the former three requirements: supply, demand and APTS representation.

Listed above are the general requirements a microscopic bus transit model should satisfy in order to simulate APTS at the operational level. Figure 3-1 is a diagram of the various APTS strategies discussed in Chapter 2 and the implications they have with respect to bus transit operations and operations simulation.

In the diagram, the interaction between the model requirements can be seen, where the APTS

- enable a variety of real-time operational strategies (e.g. holding and dispatching) that directly affect *transit vehicle movements*,
- provide valuable input to planning applications that lead to better *transit system* design (e.g. improved scheduling and route planning),
- and allow the sharing of real-time performance information with travelers to influence *demand* and improve passenger level of service (e.g. route choice)

The *APTS representation* makes possible the simulation of the real-time operational strategies and traveler information dissemination, and the measures of effectiveness provide output from the simulation with which to evaluate the performance of the APTS.

Many APTS are designed to benefit bus transit service providers in terms that are particular to transit supply (e.g. operations control, resource management, finances etc.). In general, these supply-oriented benefits can be achieved in one of two ways: through operations planning or during real-time operations. On the other hand, as is shown in Figure 3-1, some APTS interface with the user and are designed either to provide benefits directly to transit passengers or to encourage some desired traveler behavior (e.g. encourage ridesharing, advertise transit travel time savings), thus influencing travel *demand*. Figure 3-1 relates the APTS technologies to the processes that they most directly influence or affect. The model requirements listed above are necessary in order to simulate this level of interaction between APTS strategies and technologies and the supply and demand elements of the system. The measures of effectiveness generated by a simulator allow the user to determine the extent to which the planning and real-time objectives shown in the figure may be achieved.

The APTS representation requirement calls primarily for an accurate depiction of real-time information, when and where it is generated and how it is conveyed to, and put to use by, other parts of the system. The diagram demonstrates these information-based relationships. For example, AVL alone does not have any impact on operations planning, passenger travel behavior, or real-time operations. However, when AVL provides input to such other APTS technologies as traveler information systems and transit operations software (e.g. CAD), the technologies can together bring about significant improvements in planning and real-time activities and in passenger information. Thus, some APTS *provide* valuable information (e.g. AVL) without recommending or implying any course of action, while others *apply* information in order to obtain some benefit.

The model requirements identified in this chapter may be incorporated into a simulation model one of two ways, as indicated in Figure 3-1, by

- providing system variables and parameters as *input* to the model,
- or modeling *internally* the effects of APTS on system variables.

The scope of most traffic simulators is restricted to real-time operations. However, some transit system variables, such as routes, schedules and passenger demand, are products of operations planning or passenger trip planning applications and do not generally vary

Core Technologies

- Geographic Information Systems
- Automated Vehicle Location
- Electronic Fare Payment
- Automatic Passenger Counters
- Communications Systems

Applications

- Automated Service Coordination
- Transportation Management Center
- Transit Operations Software
- Traveler Information Systems
- Transit Signal Priority
- Dynamic Ridesharing

Operations Planning

Improved Scheduling
Route Planning
Cost Reduction
Revenue Increases

Transit Demand

Passenger Travel Behavior

Pre-Trip Route Choice
Pre-Trip Mode Choice
En Route Route Choice
Departure Time

Real-Time Operations

Control & Dispatching
Information Provision
Emergency Response
Incident Response
Service Restoration
Intermodal & Service Coordination
Transfer Connection Protection
Dynamic Re-Scheduling & Re-Routing

INPUT

SIMULATION

Figure 3-1 APTS impacts on transit operations and implications for simulation

during the course of a simulation period. Therefore, planning effects are best simulated by way of input to the model. APTS that interact with real-time operations and that provide real-time information to passengers, on the other hand, can be represented within the simulation using models that capture interactions

- between transit vehicles and other modes,
- between transit vehicles and passengers,
- between transit vehicles and field-installed control devices,
- between transit vehicle operators and the TMC,
- and between transit passengers and traveler information.

Capturing these behaviors within a realistic representation of bus transit systems is the ultimate objective behind the development of a list of requirements for simulating APTS. The dashed line that forms a rectangular box in Figure 3-1 encloses the processes that may be modeled within a traffic simulator. Outside of the box are those processes that may generate inputs to the model for simulating various schedule and route designs, as well as various levels and patterns of passenger demand.

In the sections that follow, 3.2-3.5, each of the model requirements, and variety of issues regarding the incorporation of the requirements into a microscopic simulator, is discussed.

3.2 Transit System Representation

Bus transit is a diverse industry, varying widely in terms of the service standards and policies held by the service provider, the activity patterns of the passengers, and the technology available to the service provider. All of these factors shape the system design of a bus transit service. Bus transit systems are also widely varied in terms of the types of service they provide. Furthermore, a single bus transit system might offer a variety of types of service. In general, bus transit system design is determined in accordance with the service standards and policies of the provider. Service standards and policies also may vary considerably from one provider to another. Therefore, it is necessary to take a generic approach to representing bus transit systems in a microscopic simulator, and to

structure the representation in a way that supports the state of transit practice and prevailing trends. Some useful transit terminology are provided in Appendix A.

The transit system representation as an APTS modeling requirement is divided into three parts for the purposes of this thesis:

- Transit network

- Schedule design

- Fleet Assignment

The three components of transit systems listed above are largely functions of service provider decision-making, behaviors and policies. A transit operations modeling effort should first have a realistic representation of the transit network, which ultimately defines where buses travel and stop in the network. The schedule design representation should reflect the state of the practice in schedule development, allowing the use to represent various aspects of the schedule, from service frequency to service timing. Finally, the generation of transit vehicle trips in a simulation model should be consistent with trip generation and vehicle assignment methods that service providers use to develop work assignments for individual vehicles.

3.2.1 Transit Network

The representation of the transit network includes the links, or paths, in the network that make up bus routes, the designs and locations of bus stops along those routes, and the designs and locations of other bus transit facilities, such as bus lanes, in the network. The definition of the transit network in a simulation model is critical to the interaction between the transit service and the passengers and the surrounding traffic environment. For example, mixed traffic, as opposed to bus lane, transit routes involve complex interactions between different modes. The representation of bus stops (e.g. single vs. multiple berth stops) can have considerable impacts on vehicle operations at stops. Bus stop design also has important implications with respect to the neighboring traffic stream. For instance, bus stops that are located in the general traffic lane, as opposed to those that are removed in a wayside bay, will require different bus operator maneuvers and stimulate different behaviors from other drivers in the network.

Furthermore, the transit network is the basis for defining schedules and pieces of work to which buses in a fleet may be assigned.

The transit network may be subdivided into three graduated levels, or scales, of representation:

6. System-wide
7. Route segment
8. Transit stop

By decomposing the bus transit network into bus stops and route segments, and by examining the system as a whole, one may observe the entire range of issues affecting bus operations. For example, bus operations at the bus stop-level are uniquely separate from, but not independent of, route segment-level operations. Passenger waiting times, bus dwell times, and boarding, alighting and crowding phenomena occur at the bus stop level. The composite effects of dwell times at a series of stops, traffic congestion and intersection delays, in turn, may be observed at the route segment level. Thus, a detailed representation of the transit network is essential for simulating a range of bus transit phenomena.

3.2.2 Schedule Design

The schedule design determines how and when buses serve the transit network. Because the purpose of this thesis is to develop bus transit models for simulating APTS that generally aim to improve transit service, a great deal of emphasis on the supply side is placed on the operational characteristics of the bus service, which is generally defined by a schedule. In order to develop a flexible representation of a transit schedule, one might consider various types of bus services, such as bus rapid transit, fixed route services and demand responsive services. The transit network generally accounts for the movement of buses in space. The bus transit schedule, however, defines the movement of buses in time. The bus transit schedule defines how, or more specifically *when*, each bus in the fleet is used to serve a network of stops and routes.

From an operational perspective, the schedule is perhaps the most important element of bus transit supply. From the schedule, passengers derive their expectations of the service, and behave accordingly. Furthermore, the schedule prescribes each bus'

assigned sequence of trips on the timeline. Pine (1998) identifies three components of the transit schedule that are most influenced by the provider service standards and policies:

1. Route structure
2. Service frequencies
3. Service timing

Route structure refers to where the bus travels in the performance of its assigned trips and relates to the transit network representation. However, service frequency refers to how often a bus passes a given stop on the route, and service timing refers to when a bus arrives at a particular location on the route. These elements of the transit schedule, combined, define how each bus is intended to move throughout the transportation network in time and space.

3.2.3 Fleet Assignment

A difficult question for transit service providers is how to assign a limited fleet of vehicles to the transit schedule. A vehicle assignment is defined as the work assignment given to a single transit vehicle for the duration of a service workday. In the context of simulation, however, it may be considered the total work assignment given to a transit vehicle for the course of the simulation. For networks where the whole of a bus route is modeled, the work assignment might involve multiple roundtrips on the route. Furthermore, in cases where more than one route is represented in their entirety, the work assignment might include interlining trips that permit a single vehicle to serve more than one route, as is done in practice.

A single vehicle's work assignment generally comprises a number of trips, which are defined in the schedule, that are linked together, forming a single path from start to finish in service of one or more routes. This method of linking successive trips together to create runs is referred to as "blocking", where blocks are feasible series' of scheduled trips. The blocking process is a critical element of the bus transit scheduling because it has strong implications with respect to operating costs. Various APTS applications, such as transit operations software, might be used to improve the blocking process to reduce

costs. Therefore, it is important that a simulation model provide a reasonable representation of individual vehicle work assignments.

3.3   Transit Vehicle Movement and Interactions

Transit vehicle movement and interaction refers to bus operator behavior and the behavior of other drivers in the proximity of buses. In order to accurately simulate bus operations, it is not enough simply to model the predetermined paths of buses along fixed routes. In general, a fixed-route bus will travel its assigned route, and therefore *where* a bus moves en-route through the network will not vary. However, *when* and how frequently buses arrive at specific locations along the route is not only a function of the schedule, but is susceptible to various random disturbances. These random variables include the prevailing traffic conditions on and adjacent to the route (i.e. congestion), traffic control (e.g. traffic signals determine the throughput capacity of each movement) and passenger demand (i.e. boarding and alighting passengers determine dwell time). Many service reliability and quality of service problems that plague mixed traffic bus services generally arise from these operational disturbances, which cause the bus to deviate from the intended schedule.

Therefore, in order to account for this dynamic that is a product of the interaction between the bus and the surrounding traffic and transit environment, the behavior of the bus operator and the behavior of non-transit vehicle drivers are considered together as a critical APTS modeling requirement. Bus operators must perform various maneuvers throughout the course of their assigned trips. For mixed traffic bus services, these maneuvers include pulling into and out of the mixed traffic stream. These kinds of bus maneuvers can have a considerable impact on the flow of traffic in neighboring lanes. Similarly, the flow of traffic in neighboring lanes affects the bus operator's behavior in approaching and leaving each stop. Consequently, the behaviors of bus operators, and also the behaviors of private automobiles in the proximity of buses, greatly affect the manner in which the buses operate and the manner in which the service is delivered (i.e. supplied) to the customer. Vehicle movement in this thesis is considered in two parts: behavior between stops and behavior at and near stops.

3.3.1 Behavior Between Stops

Vehicle movements between bus stops refer to bus operator driving behaviors that control the vehicle's trajectory from one stop to the next, after it has pulled out of a stop and before it has begun to pull into the next stop. The vehicle's path is decided by the route structure, but the operator determines the more microscopic movements along the predefined route, such as lane changes and accelerations. Driving behavioral modeling is dominated by acceleration and lane-changing models, which are typically complemented by more detailed models of gap acceptance, merging, and yielding. In reality, one might not expect the driver decision-making that drives acceleration behavior to be fundamentally different for bus operators than for private auto drivers. In a car-following regime, like other drivers, the bus operator must apply the necessary acceleration/deceleration in order to negotiate a safe following distance from the vehicle in front. In free-flow, the bus operator's chosen speed might be decided by the operator's desired speed or by service provider policy. Either way, the acceleration models for bus operators and other drivers might be assumed to be identical.

Lane-changing behavior, on the other hand, is fundamentally different between bus operators and other drivers, and simulation models should reflect this difference. In general, lane-changing theory views the driver similarly to the way economic theory views the consumer. In other words, a driver chooses a lane in a way that maximizes his or her benefit. Lane-changing theory assumes that each driver aims to minimize his or her travel time, and thus chooses to make discretionary lane changes based on the perceived utility of the alternative lanes, which is a function of the relative speed of the vehicles in the target lane(s). Bus operators, in contrast, have no personal origin or destination, but rather travel their predefined routes with the aim of serving passengers at each stop according to an assigned schedule.

A bus operator might make discretionary lane changes between stops to increase travel speed according to the same decision-making processes as other drivers, albeit with a preference toward the lane with bus stops. However, mandatory lane-changing decisions will largely govern the bus operator lane-changing along a route. A bus operator must make mandatory lane changes in order to be in the appropriate lane when the bus arrives at each stop. Thus, the route structure, the location and spacing of stops

along the route dictate to a great extent bus operator lane-changing. Other factors affect bus operator lane-changing that do not affect other drivers, such as the presence of bus lanes and HOV lanes. Likewise, there are factors that affect private auto driver lane-changing that do not affect bus operator lane-changing. For instance, as previously discussed, one might expect that private auto drivers traveling behind a bus in a lane that contains bus stops will attempt to move out of the lane and overtake the bus in anticipation of the bus' routine stopping and starting at those stops. Silva (2001) proposes that private auto drivers change lanes to overtake buses at the earliest opportunity.

There are other differences between bus operator behavior and private auto driver behavior. For example, some simulation packages model the variation in familiarity with the network among the driving population. Familiarity with the network translates to various behaviors such as how far in advance of a turn or exit from the current roadway a driver changes lanes in order to make that turn or exit. Bus operators should be very familiar with the network, particularly with their assigned route, and would likely anticipate and execute the necessary lane-changes in advance. A failure to capture bus operator familiarity might cause a simulation model to overstate congestion when buses make late lane change maneuvers. Furthermore, it is not necessary that bus operators evaluate route choice alternatives as other drivers might, since the buses' paths are fixed.

3.3.2 Behavior At and Near Stops

Behavior at and near stops encompasses all behaviors in which a bus operator engages in order to pull into a stop, serve passengers, and reenter the traffic stream. By far, the majority of the attention in the literature has been dedicated to dwell time, or the period of time during which a bus is stopped at a bus stop to serve passengers. Dwell time consists of dead time and service time. Dead time is the sum of time spent stopped with the doors closed and the time spent to open and close the doors. The service time is the span of time during which the doors are open for passengers to board and alight. The amount of time a bus spends at a stop can depend on many factors, including weather, bus stop design and passenger demand. The main determinant of dwell time, however, is passenger demand. Levinson (1983) found that buses spend as much as 26 percent of

their total travel time at bus stops. Hence, the time it takes to board and alight passengers can have a profound impact on bus operations.

However, vehicle movement *near* bus stops can also have a serious impact on the surrounding traffic stream and on vehicle progression. Bus operators must make special maneuvers in order to pull into and, more particularly, out of bus stops. Namely, the behaviors of other vehicles near bus stops are critical when a bus operator is attempting to pull out of the stop. Unrealistic, excessive delays may arise if a simulation model does not reflect the way drivers in the adjacent traffic stream yield to exiting buses, and thus may cause undue disruption of the bus' progression. The yielding behavior of other drivers, in turn, can have significant consequences with respect to congestion in the general traffic stream. These kinds of considerations should be made when modeling behavior near stops.

3.5 Transit Demand Representation

Passenger demand for bus transit services plays a critical role in bus transit operations. Recalling from Section 3.4, passenger behavior is the most significant determinant of bus dwell time, the duration of time a bus remains stopped at a bus stop to serve passengers. Therefore, it is important to understand, and, in a simulation model, to represent realistically, the nature of passenger demand. Passenger demand is generally considered to be random. For instance, passenger demand can be highly variable at the route level, the sub-route (or route segment) level and the bus stop level. The geographic distribution of passenger demand is subject to the local land use patterns and the locations of activity centers along a route. Thus, passenger demand may be heterogeneously distributed across the various segments on a single route.

Furthermore, passenger demand may have considerable temporal variability. For example, passenger demand might vary by time of day (e.g. peak and off-peak) and day of the week (e.g. weekday vs. weekend) and is subject to spiking due to special events (e.g. sporting events). The random, variable nature of passenger demand has a profound effect on vehicle progression along a route, and on its adherence to the schedule. Large passenger demand (boarding and alighting passengers) at a bus stop and crowding on the

bus might cause delays at the stop, thus preventing the bus from departing on schedule. A lack of demand at a bus stop, in the absence of dispatcher intervention or operating procedures that call for holding, might cause the bus to depart early and therefore get ahead of its schedule.

It is important in a bus operations simulation model to capture the way that passengers use the service. At a lower level, passenger boarding, alighting and crowding behavior affects bus operations at stops. At a higher level, however, the number of passengers boarding and alighting depends on passenger arrival patterns, which is usually a function of the type of service. For example, it is generally assumed that transit passengers tend to arrive more randomly as the service becomes more frequent and irregular. On the other hand, as the service becomes more regular and infrequent, passengers tend to rely more heavily on the schedule and thus time their arrivals at stops closer to the scheduled vehicle arrival time in order to minimize waiting time.

Jolliffe and Hutchinson (1975) divided transit passengers into three categories: the proportion q who arrive coincidentally with the bus and thus have no waiting time, the proportion p who are familiar with the schedule and arrive close to the vehicle arrival time and wait on average w_{min}, and the proportion (1-q)(1-p) who arrive randomly and wait on average w_{rand}. When passengers arrive randomly, $w_{rand} = \mu(1+\sigma^2/\mu^2)/2$, where μ and σ are the mean and standard deviation of the time headway between buses, respectively. Based on measurements taken at bus stops in London, Joliffe and Hutchinson estimate p as a function of the service characteristics:

$$p = 1 - e^{-\lambda g},$$

where $g = w_{rand} - w_{min}$. The value of g is the potential to reduce waiting time, and increases as the time headway between buses increases. Therefore, p increases when bus services become more infrequent. The value of λ was determined to be 0.131 and 0.015 for peak and off-peak conditions, respectively, confirming a priori expectations that, during the peak, more passengers are familiar with the schedule and arrive so as to minimize waiting time.

Joliffe and Hutchinson's findings underscore the importance of representing both the detailed characteristics of the bus service, such as schedule timetables, and the passengers in a simulation model. The arrival behavior of passengers at bus stops

determines the number of passengers waiting to board at each stop, and thus the delay each bus experiences at a stop. At the same time, the characteristics of the bus schedule, such as the design headway, influence the way passengers arrive at a stop. This dynamic interaction between the passenger and the service is the subject of a host of APTS applications, including traveler information systems, and has significant operational implications with respect to APTS that mean to monitor and control bus operations in real time.

3.6   APTS Representation

Transit service providers in the U.S. employ a wide range of technologies designed to aid the monitoring and control of bus operations. Other technologies that provide static or real-time information to passengers are increasing in popularity. Various APTS technologies, whether for collecting information, applying information (e.g. for real-time control) or disseminating information, differ widely in their designs and their operations. Some APTS are designed to function offline and are not directly involved with transit operations in real-time. Among these offline technologies are Itinerary Planning Systems (fleet management, transit operations software) and some automated service coordination applications. By using the outcomes of these offline applications as input to a simulation model, as is shown in Figure 3-1 earlier in this chapter, one may evaluate the impacts of the strategies on transit operations, but they do not involve any real-time exchange of information that may be simulated at the operational level.

This discussion is focused, however, on online APTS technologies, those that are used simultaneously with bus operations. The online APTS technologies that make up the bus surveillance system serve as the link between the supply and demand components of the bus transit system. Surveillance includes the sensor technologies, and their governing logic, used by transit service providers to monitor the performance of the system. These sensor technologies might include installed roadside bus sensors or automated vehicle location technologies (e.g. GPS). A surveillance system might also include communications technologies that allow the bus to transmit information to the

TMC. Using the surveillance system, transit service providers can monitor bus progression and make informed decisions regarding real-time control of each bus' movement and behavior (e.g. dispatch or hold at a bus stop).

The surveillance system may also be used to generate real-time input to various APTS control strategies, such as conditional bus signal priority, and various information systems, such as in-terminal/wayside traveler information. In order to simulate APTS at the operational level, a traffic model must be able to mimic the functionality of the technologies as they operate in the real world. The surveillance system depends on two things: the technical capabilities of the technologies and the institutional utilization of those technologies in practice. Three important, emerging APTS applications in bus operations surveillance are GIS, AVL and communications systems. The discussion of GIS, AVL and communications systems in Chapter 2 suggests that the state of the practice varies considerably. For instance, vehicle location is collected at the TMC via methods such as polling and exception reporting and, in methods like polling, vehicles might be polled sequentially and/or simultaneously and at varying intervals.

There are a number of AVL application case studies in the literature, documenting the high level makeup of the system and their benefits. However, few have gone so far as to divulge the technical details of the system in operation. Since the operating characteristics of AVL and other transit surveillance systems vary not only by the system's technical specifications, but also by the way service providers put those systems to use in practice, it is important to base a modeling effort on the functional architecture (e.g. where information is generated and how it is shared) adopted by the service provider for each application rather than on the technology's own intrinsic capabilities. Furthermore, since the performance characteristics of various APTS surveillance technologies vary widely from application to application, a generic and flexible bus operations model should be able to replicate the types of information (e.g. location, speed, load) that the technologies produce and mimic the mechanism for sharing that information between the components of the bus system (e.g. TMC, control devices, vehicles).

3.7 Measures of Effectiveness

Traffic simulators generate traffic measures of effectiveness that are used to evaluate alternative traffic management strategies or geometric designs. Likewise, when simulating APTS, it is important to consider the benefits and costs of implementing a particular APTS application. Since most APTS are designed to improve in one way or another transit performance or passenger level of service, an APTS simulator should produce transit measures of performance that may be used to determine the extent to which candidate APTS strategies achieve the system's objectives. These objectives might involve benefits, or costs, that are produced at various levels of the transit system, including:

- System level
- Route segment level
- Bus stop level
- Vehicle level
- Passenger level

The Transit Capacity and Quality of Service Manual (TCQSM) defines transit performance measures as qualitative or quantitative factors used to evaluate a particular aspect of transit service (Kittelson & Associates, 1999). Qualitative factors include, for example, passenger comfort, safety, and amenities at bus stops. Quantitative factors might include monetary considerations, such as cost savings and revenue increases from increased ridership, or service delivery measures, such as on-time performance and headway adherence. The bulk of expected APTS benefits are quantitative gains that accrue either to the service provider (e.g. cost savings, revenue increases) or to the passenger (e.g. reduced waiting and in-vehicle time). APTS also produce benefits that occur in different parts of the network, such as at bus stops (e.g. dwell time reduction), along a route segment (e.g. travel time, headway variability) and at the system level (e.g. transit vs. auto travel times). Therefore, performance measure output from traffic simulation should include data about the different elements of the system in order to draw meaningful conclusions about the performance of APTS.

A variety of measures are recommended in the literature for evaluating transit performance. The Federal Transit Administration conducted a study to determine the state of the practice of bus route evaluation standards in North America (Benn, 1995). The study divides bus route evaluation standards into 5 categories:

- Route design – bus stop location, spacing, coverage, network connectivity
- Schedule design – number of standees, waiting time for a transfer, span of service
- Economics and productivity – passengers per mile, passenger-miles, subsidy per passenger
- Service delivery monitoring – on-time performance, headway adherence
- Passenger comfort and safety – passenger complaints, missed trips, etc.

With the exception of service delivery monitoring standards and number of standees, the categories above say very little about vehicle performance on a route at the operational level. The evaluation standards listed above mainly describe the performance of a route at the system level to determine whether a route is meeting the expectations of the customers and of the service provider.

The TCQM gives a similar list of transit quality of service measures, but with a broader view of overall transit quality of service, taking into account the operator (service provider), passenger and vehicle points of view, as opposed to a route-based focus. Some of the quality of service measures that are relevant to APTS operations include total trip time, passenger loads (e.g. standing and crowding), and reliability. These three measures are descriptive indicators of how vehicles operate and passengers are served on a given route. Appearance, comfort, amenities, pedestrian environment and other such qualitative measures recommended in the TCQSM are outside of the scope of traffic simulation.

Along with the emergence of APTS has come an increasing awareness of transit reliability phenomena such as bus bunching, which tend to degrade transit performance and the passenger experience. The expected benefits shown in Figure 3-1 indicate a need for a new set of standards for measuring operational transit performance. The TCQM offers yet another system for categorizing transit performance measures that is better suited for evaluating APTS. The TCQM examines quality of service at the bus stop

level, at the route segment level and at the system level. Service quality at bus stops includes measures such as passenger loads, which affect boarding and alighting times, and reliability, such as schedule and headway adherence. Service quality at the route segment level includes measures such as reliability, transit speeds and travel times. Finally, service quality at the system level entails such measures as transit/private auto travel time and speed comparisons.

Often, special measures of effectiveness, which may not apply broadly to all APTS, are necessary for evaluating the performance of a particular APTS application. In these cases, special consideration should be made for the intended purpose of the strategy and how its application affects, both intentionally and unintentionally, bus operations and traffic in general. Transit signal priority is one such example. Dale et al. (1999) recommends a set of 9 measures of effectiveness, shown in Table 3-1, for evaluating transit signal priority.

Table 3-1: Transit signal priority measures of effectiveness

Measure of Effectiveness	Description
Intersection Control Delay	Total delay to all vehicles in queues at traffic signals
Minor Movement Delay	The delay at traffic signals to cross-street movements and protected main-street left turns
Minor Movement Cycle Failures	The event that vehicles performing minor movements arrive during a red interval and are unable to clear the intersection during the following green
Bus Travel Times	The time it takes a bus to travel the length of a route or route segment
Bus Schedule Reliability	The use of travel time variability (standard deviation) as an indicator of reliability
Intersection Bus Delay	Average delay to buses at an intersection
Average Person Delay	Intersection control delay, intersection bus delay, average automobile occupancies and bus loads to determine delay in seconds/person
Vehicle Emissions	CO and NOx emissions on a segment basis
Accidents	Transit vehicle accident frequency as a safety measure

The choice of these measures of effectiveness is tailored to the case of transit signal priority, which has raised a policy debate regarding the delay that transit signal priority causes to conflicting movements at intersections. Thus, the delay to cross-street movements, for example, is important for determining the impacts of priority on other

vehicles in the network. However, the performance measures in Table 3-1 do not take into account passenger experiences at the bus stop (e.g. waiting times), but do consider the in-vehicle delay to individuals, both transit riders and auto drivers. Like transit signal priority, most APTS may have a variety of network effects with respect to both the transit network and the greater transportation network that may vary from application to application. Nevertheless, these network effects should be considered as part of the evaluation process.

Chapter 4

Bus Transit Modeling Framework

Chapter 3 sets forth the bus transit model requirements that a simulation model must represent in order to simulate APTS applications. This chapter provides some background into the state of the art of bus transit operations simulation and proposes a framework for incorporating the model requirements into MITSIMLab, an existing microscopic traffic simulation laboratory. Chapter 5, then, discusses the detailed implementation of the requirements into the modeling framework.

4.1   Background: Bus Transit Simulation

Traditionally, bus operations in microscopic simulators have been the subject of little or no rigorous model development and calibration. Silva (2001) conducted a review of a representative group of microscopic simulation models and concluded that a detailed representation of bus operations and the interactions between buses and other vehicles has been largely ignored and unrealistically simplified. Traffic simulation models have generally treated buses as little more than larger vehicles that periodically stop, or don't stop at all, at certain locations in the network. These "larger vehicles" have behaved just like any other vehicle in the network and have had no explicitly designated route or schedule. Traditionally, transit passengers have also not been represented. Instead, overly simplistic dwell times at stops have been used that do not capture the effects of passenger demand variability and randomness in the network.

The minimalist representation of buses and passengers, therefore, has precluded the simulation of transit surveillance technologies. For instance, transit surveillance technologies such as AVL typically are used to identify specific vehicles and to measure vehicle performance against a known work assignment. It is not meaningful to simulate AVL in a model where buses move anonymously through the network. In recent years, many traffic simulation software developers have begun efforts to improve the representation of bus transit operations. Most of these efforts are the effect of growing interest in more popular APTS applications, such as bus signal priority.

Bus transit operations modeling in microscopic traffic simulation has undergone considerable change in recent years. Generally, the aim of recent bus transit simulation improvements have been to better model the random elements that affect vehicle progression, such as travel times, traffic signal delay and passenger demand, in order to better capture transit phenomena such as bus bunching. The impacts of traffic congestion and signalized intersection delay on transit vehicles are generally assumed to be well represented. Thus, a lot of attention has been dedicated to the representation of passenger demand, and its effects on dwell time at stops. More recently, research has been conducted regarding mixed traffic interactions, such as bus-automobile interactions, and the behaviors of bus operators as they pull into and out of bus stops. Research into the interactions between bus operations and other modes of traffic (e.g. private automobile) suggests that a better representation of traffic congestion in a multi-modal traffic environment may be achieved.

Various microscopic traffic simulation programs exist that are able to represent bus operations at various levels of detail. In 2000, Barrios et al. (2000) reviewed four simulation software packages, CORSIM, VISSIM, Paramics and SIMTRAFFIC. The purpose of the review was to choose the package that could most accurately represent bus operations for the evaluation of various alternative design improvements to the Transbay Terminal, a transit hub in San Francisco, California, that serves 41 bus routes and 20,000 passengers per day. CORSIM, VISSIM and Paramics are able to model bus routes. Each of these three simulators are able to model random dwell times at stops, but VISSIM alone allows the user to include pre-specified departure times for representing layover time at a terminal. Similarly, only VISSIM was able to model some bus operations in the

terminal, such as bus staging on the left side of the road, where the vehicle waits before pulling into a bus stop on the right side of the road. Each of these simulators is able to model bus interactions such as queuing, yielding and stopping in the terminal.

The representation of bus transit in these and other microscopic simulation software packages have since been enhanced, indicating a shift away from traditional, simplistic bus transit modeling and an increasing emphasis on bus transit operations simulation. For example, the representation of bus operations in CORSIM has undergone recent changes, allowing buses to depart from stops based on both a scheduled departure time and passenger boarding and alighting demand. CORSIM also accepts time-dependent passenger stop-to-stop origin-destination matrices as input. The numbers of boarding and alighting passengers are calculated based on the OD matrices, and dwell times at stops are determined by calibrated average boarding and alighting rates. CORSIM, now, may also produce detailed transit operations-related output such as travel time, reliability (e.g. deviations from schedule, headway variability, etc.), and passenger waiting time. With the improved bus operations representation, CORSIM was better able to capture real-world transit phenomena, such as the increase in standard deviation of headways at stops with increasing number of stops along a route and with increasing passenger demand (Ding et al., 1999).

Still more microscopic traffic simulation models exist that offer, or are in the developing stages of, an advanced representation of bus transit operations. The literature documenting these development efforts is scarce, especially in cases where the models are developed by private enterprises. However, literature dedicated to more specific aspects of bus operations, such as dwell time modeling, is available and is discussed in Chapter 5. In the following sections is a description of MITSIMLab, a pre-existing microscopic traffic simulation laboratory, its framework, and an expanded framework for incorporating APTS simulation requirements into the simulator.

4.2 Introduction to MITSIMLab

The objective of this research is to advance the bus transit operations representation in a microscopic traffic simulation laboratory in order to enhance that simulator's capacity for evaluating APTS at the operational level. The modeling

requirements identified in Chapter 3 are incorporated into MITSIMLab, a microscopic traffic simulation laboratory developed for the design and evaluation of advanced traffic management systems (ATMS) and advanced traveler information systems (ATIS) (Yang, 1997). MITSIMLab serves as a laboratory for testing and refining alternative ATMS and ATIS designs, which include APTS applications. However, MITSIMLab, like many microscopic simulation packages until recently, has lacked detailed bus transit models needed to simulate complex bus operations and, thus, to evaluate ITS applications in public transit. In terms of general vehicle traffic, however, MITSIMLab is based on sophisticated behavioral models, including driver behavior and route choice, that capture a range of complex decisions that drivers make before departing and en route to their destination.

MITSIMLab has a modular structure, which makes it suitable for adding new functionality, such as bus operations, to the model. The general evaluation framework is illustrated in Figure 4-1.
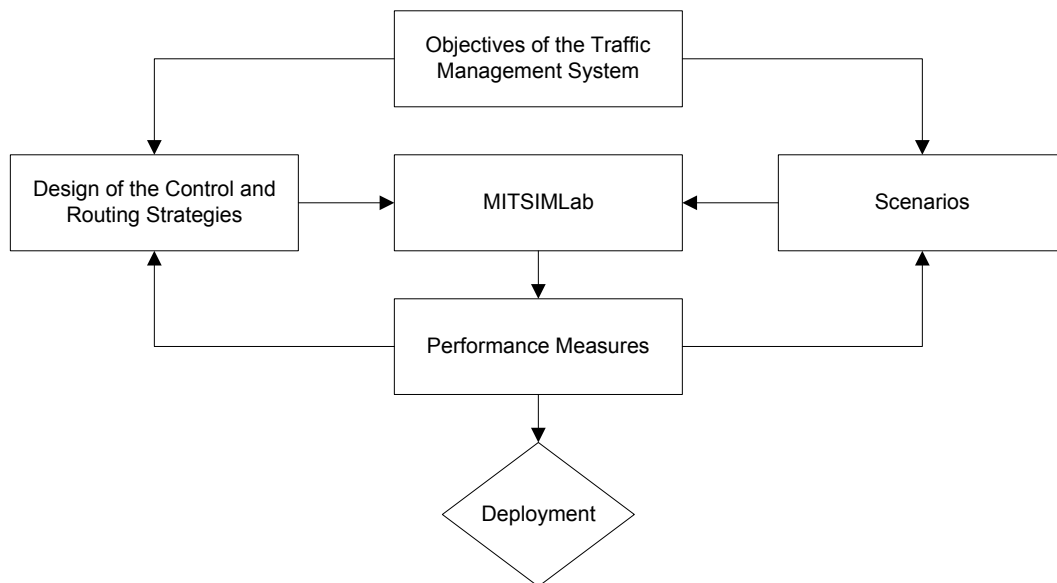
Figure 4-1: MITSIMLab Evaluation Framework

With the inclusion of the bus transit operations models and the pre-existing driver behavioral models, the end result is a flexible, multimodal simulation tool with which the user may evaluate the performance of APTS strategies under a wide range of traffic conditions. The user may simulate an APTS strategy in a number of scenarios that test

the robustness of the system, observe the measures of performance generated by the simulation, and subsequently make refinements to the system in order to achieve the original objectives.

4.2.1 MITSIMLab Structure

Central to MITSIMLab's design is the interaction between the driver and the ATMS under evaluation. MITSIMLab models the driving and traveling behaviors of individual drivers on a road network, which may be layered with a variety of traffic sensor and surveillance technologies and control devices. Simultaneously, MITSIMLab simulates the logic of the traffic management strategy, which governs the performance of the control and guidance devices in the network to which the drivers react. MITSIMLab is made up of three main components:

1. Microscopic Traffic Simulator (MITSIM)
2. Traffic Management Simulator (TMS)
3. Graphical User Interface (GUI)

Figure 4-2 illustrates the interactions among MITSIMLab's components.
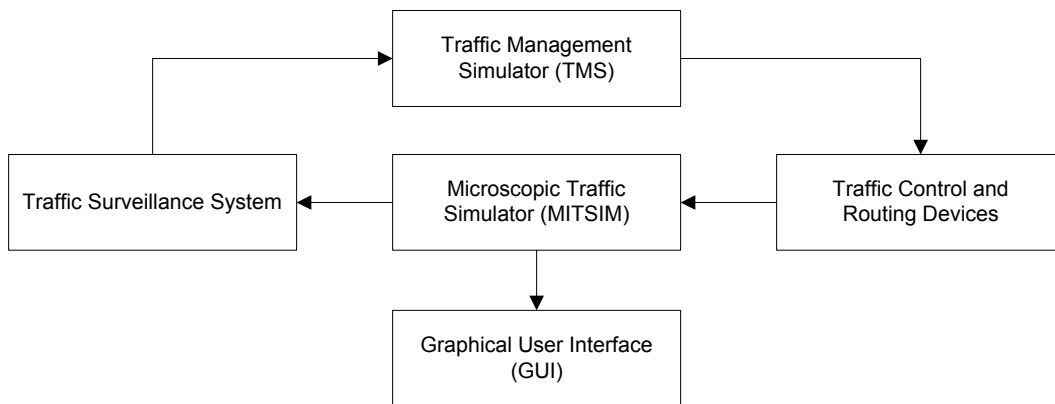
Figure 4-2: MITSIMLab components and interactions

MITSIM simulates the movements of individual vehicles, the state of the traffic control and routing devices, driver reactions to those devices, and the traffic surveillance system as it detects and measures vehicles as they move through the network. At the same time, TMS receives surveillance data from MITSIM as input to the strategy under evaluation, calculates a response according to the logic of the strategy, and communicates to

MITSIM the corresponding adjustment of the control and routing devices. As MITSIM and TMS interact, the GUI displays, through vehicle animation, evolving traffic conditions on the network. Thus, the user may use a combination of the GUI animation and output measures of effectiveness to judge the performance of a candidate strategy.

4.2.2 Microscopic Traffic Simulator (MITSIM)

MITSIM represents the physical components of the traffic environment and their behaviors. Some of the more important elements of MITSIM, which are relevant to bus operations, include the network components, travel demand and route choice, and driving behavior. Network components include the road network geometry, vehicles, and the traffic control and surveillance devices. Each driver is assigned a set of attributes that describe the driver's behavior, including desired speed, familiarity with the network, and willingness to yield to other vehicles. Likewise, vehicles have their own characteristics, including size and acceleration capabilities. Travel demand is simulated using origin-destination matrices given as input to the model. Drivers make route choices that may be based on historical (e.g. previous experience) or real-time travel time information and that determine their paths through the network. Bus operators, however, may choose paths differently, or not at all, since the service provider decides their routes.

Driving behavior models in MITSIM determine acceleration, lane-changing and other behavior-based decisions that drivers make based on the surrounding traffic environment. Every time step (typically 0.1 seconds) during a simulation, MITSIMLab evaluates the state of every vehicle in the network and determines acceleration and lane-changing actions. MITSIM considers each vehicle in the network to be in one of three acceleration regimes: free flow, car-following and emergency. The free flow acceleration regime prevails when there is either no lead vehicle in front of the subject vehicle or the lead vehicle is sufficiently far ahead that it does not influence the subject vehicle's behavior. In the free flow case, the driver travels at his/her desired maximum speed. Car-following models, the most complex of the acceleration models, dictates acceleration decisions when a lead vehicle is near enough to the subject vehicle that the subject vehicle must accelerate or decelerate in order to maintain a safe following distance. The car-following regime is the most critical acceleration model, since it determines

acceleration behavior in congested conditions.   Finally, the emergency acceleration regime takes precedence when a driver must brake in order to avoid a collision.

Bus acceleration behavior is probably not very different from that of other drivers, since it is primarily a function of elements that are out of the driver's control, such as the surrounding traffic environment, rather than the driver's trip purpose. The discussion in Chapter 3 of bus operator behavior between stops suggests that, since bus operator lane-changing is largely a function of the route structure rather than a personal trip purpose (e.g. minimize travel time between work and home), lane-changing behavior is probably most in need of improvement in order to reflect the driving behavior of bus operators. Figure 4-3 illustrates the lane-changing model in MITSIM (Ahmed, 1999).
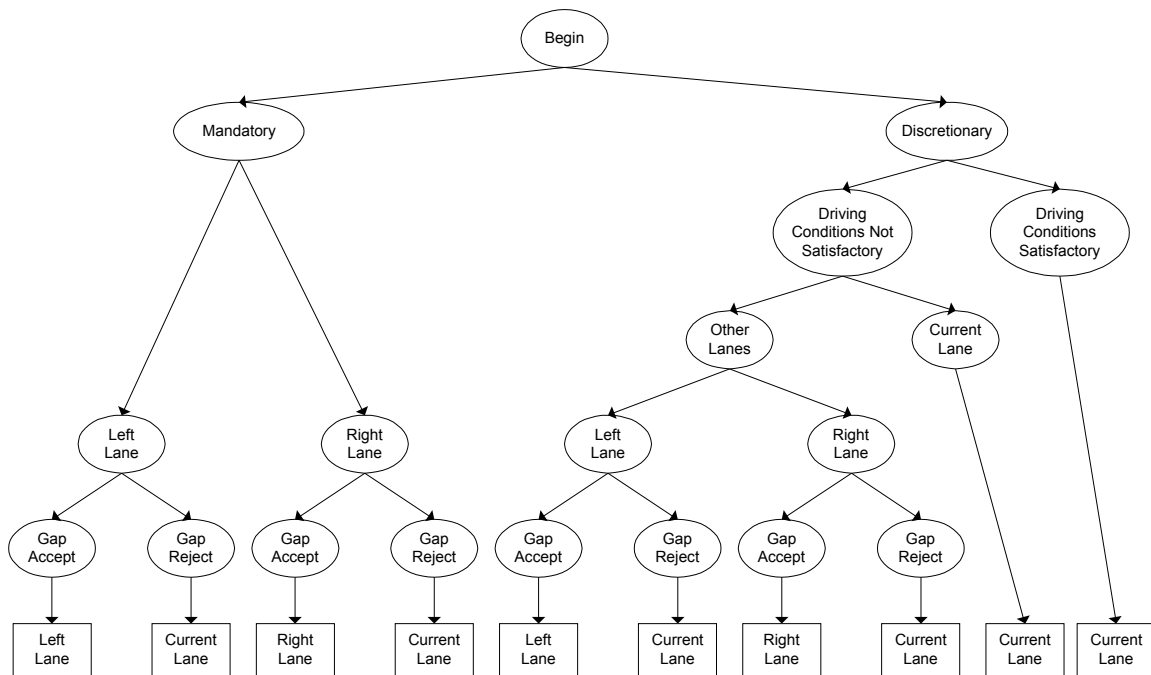
Figure 4-3: Lane-changing model in MITSIM

Drivers first determine whether a condition requires that they make a mandatory lane change (e.g. to reach a lane connected to their path downstream) and whether to respond to the mandatory condition. If no mandatory condition exists, or the driver chooses not to respond to the mandatory condition, a discretionary lane change is considered. Because buses are generally larger, slower and less maneuverable than other vehicles, bus operators may respond to mandatory conditions earlier than other drivers.

When a discretionary lane change is considered, the driver first decides whether the current driving conditions (e.g. speed) are satisfactory and, second, whether the conditions in any adjacent lane are preferable (e.g. offer gains in speed). When a driver is responding to a mandatory condition or has decided that other lanes are preferable to the current lane, the driver considers changes to the left and/or right, depending on whether those lanes exist. Once a change to the left or right has been decided, the driver evaluates the gap in the target lane and either accepts or rejects it according to the gap acceptance model. This lane-changing decision-making process may generically be applied to buses as well, but many factors that are unique to transit vehicles may warrant mandatory lane changes or render current conditions unsatisfactory.

4.2.3 Traffic Management Simulator (TMS)

TMS executes the logic of the traffic management system under evaluation. TMS has a generic framework that allows it to simulate a variety of management strategies. A diagram of this framework is shown in Figure 4-4.
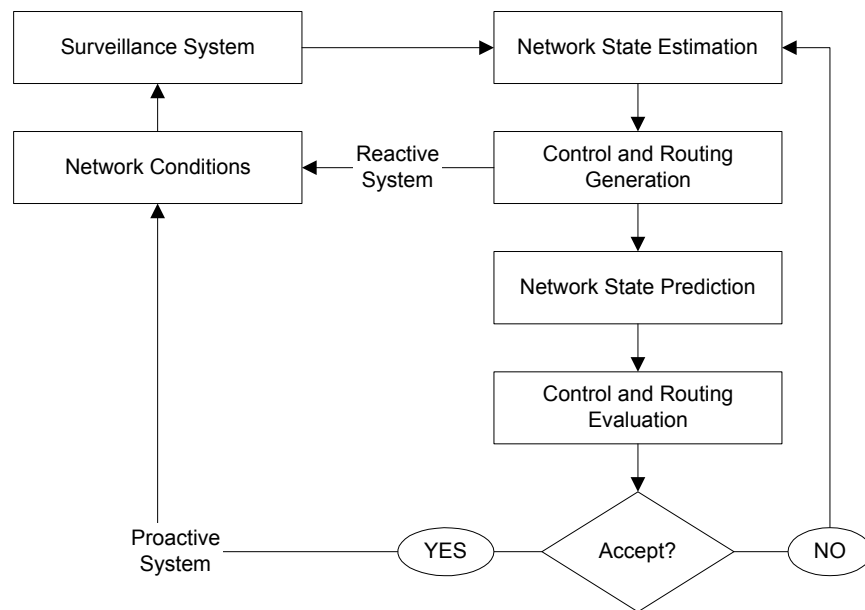
Figure 4-4: Traffic Management Simulator framework

MITSIMLab is able to represent a wide range of traffic control and route guidance systems, including signalized intersection control, variable message signs (VMS), and in-

vehicle route guidance. Proactive and reactive traffic management strategies, illustrated in Figure 4-4, can accept real-time traffic data from MITSIM and adjust the display or state of those traffic control and route guidance systems. Proactive strategies are those that use incoming traffic data to generate responsive actions, predict the state of the network that is likely occur in the event that the action is taken, and adjust the strategic action until an acceptable solution is determined. Reactive ITS strategies generate a response directly to the estimated state of the network, without any predictive adjustment. Thus, the flexible TMS framework may be used to simulate a variety of online APTS strategies that use real-time performance data to develop reactive or proactive responses to service disruptions.

An example of TMS' flexible framework is its generic signal controller, which supports a wide variety of intersection control types, including NEMA, Model 170 and European standards (Davol, 2001). The overall logic of the generic controller is shown in Figure 4-5.
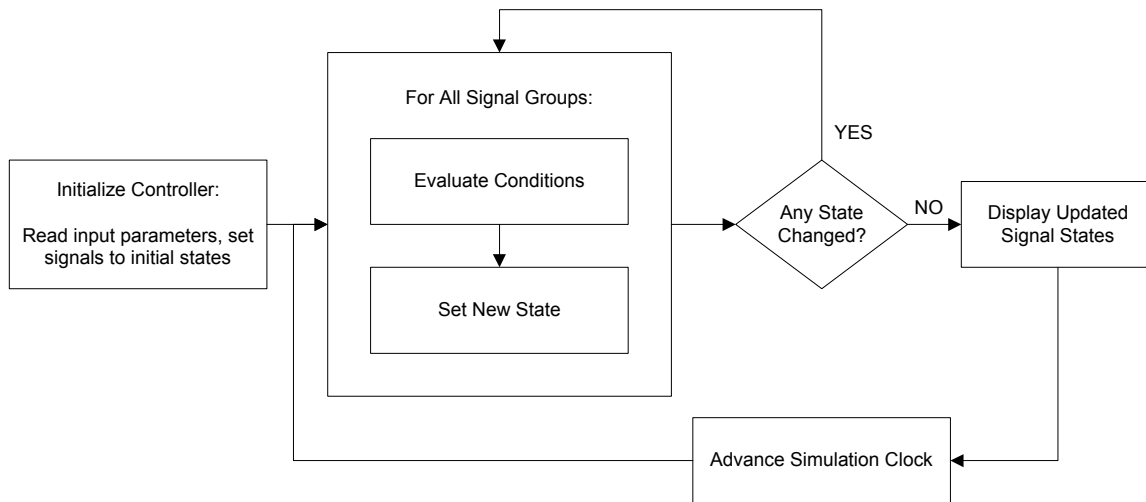
Figure 4-5: The generic controller's overall framework

The generic controller is also capable of representing isolated and coordinated control, pre-timed, actuated and adaptive control and transit signal priority. The basic structural unit of the generic controller's logic is the signal group, where a signal cycle is divided into groups of vehicle movements rather than distinct time periods (i.e. phases). Signal groups in the controller store current information about their current status and their

relationships to other groups, including current indication (e.g. red), current action (e.g. extending green time for a vehicle that has passed over a sensor), the next indication, the group's conflicting movements, and sensor data. At every time step in the simulation, MITSIMLab evaluates the current status of each signal group with respect to the logic conditions that govern each signal's indication. If a condition is met that requires the state of a signal to be changed, then the controller iterates through all other signal groups again to check whether the change will require other groups to be changed (e.g. due to conflicting movements). Some of the conditions that may warrant changing one or more signal indications are when a maximum green time at an actuated signal has been reached and when an approaching transit vehicle has called for, and has been granted, priority.

4.2.4 Graphical User Interface (GUI)

The GUI and the measures of effectiveness produced by MITSIMLab allow the user to observe network conditions during a simulation and manipulate a wealth of traffic data, respectively, in order to judge the performance of the candidate management system. The output data generated by MITSIMLab ranges from vehicle-level data, such as trajectories and travel times, to segment-level data, such as average speeds and vehicle counts. Thus, transit-specific measures of performance may be extracted from MITSIMLab's standard outputs and new transit-specific outputs may be developed in order to compare transit and network-wide performance under a variety of APTS designs.

Transit measures of effectiveness used to evaluate APTS strategies with respect to transit and network performance are incorporated into the GUI/MOE module in MITSIMLab. The detailed implementation is discussed in Chapter 5.

4.3   Framework

The general framework adopted for modeling bus and APTS operations in MITSIMLab is modeled after MITSIMLab's existing framework for traffic flow and ATMS and ATIS simulation. The objectives of the overall bus transit modeling framework are commensurate with MITSIMLab's original design: to simulate at a high level of accuracy and detail the continuous and complex interactions between individual

drivers, surveillance technologies, traffic management strategies and control and information dissemination devices in the network. The proposed bus transit framework is an expansion and an advancement of the existing MITSIMLab framework shown earlier in Figure 4-2. The new bus transit operations capabilities are built into MITSIMLab's original framework to achieve the framework shown in Figure 4-6.
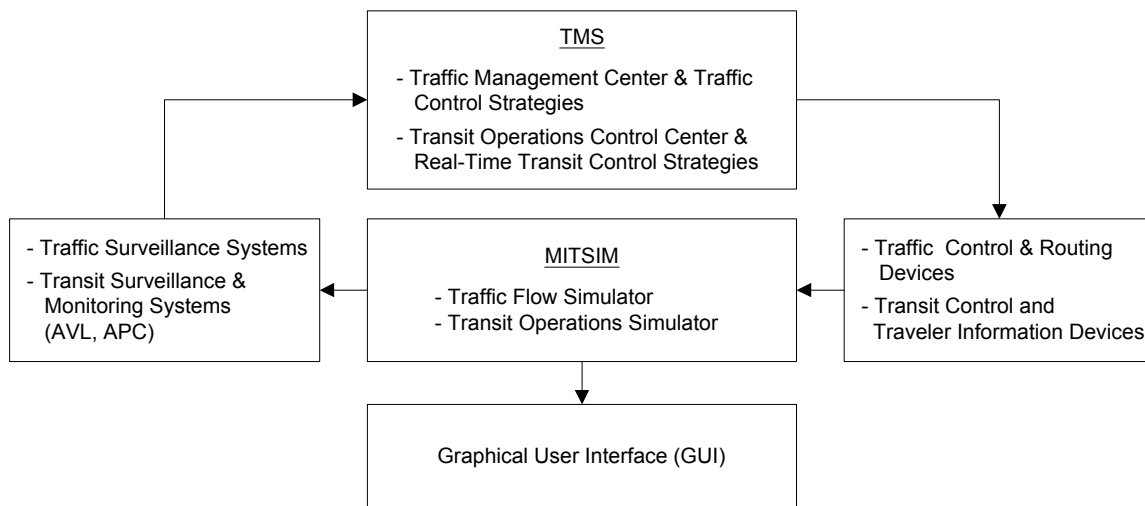
Figure 4-6: Bus transit and APTS modeling framework

The proposed generic framework affords a large amount of flexibility in terms of the range and variety of APTS solutions that may be tested.

At the center of the model is the bus transit operations simulator, which simulates the movements of individual transit vehicles through the network in performance of their assigned pieces of work. The framework, and the quality of the output measures of performance, relies heavily on MITSIM's ability to realistically represent transit vehicle progression in the presence of a diverse system of influences, interactions and disturbances. The new, expanded framework is not a trivial pursuit, for its intent is to capture the dynamic nature of two very different and behaviorally complex modes of transportation, bus and private auto, in a common, complex and multimodal traffic environment. Section 4.3.1 summarizes the modeling requirements for APTS simulation, and Sections 4.3.2-4.3.5 describe the methodology for incorporating those modeling requirements into the MITSIMLab framework.

4.3.1 Transit Operations Simulator

MITSIM, the traffic flow simulator in MITSIMLab, represents the road network as a system of links and nodes and simulates the movements of individual vehicles through the network. The modeling effort in this research extends the role of MITSIM to that of transit operations simulator. MITSIM as a transit operations simulator represents the physical portions of the transit network (e.g. bus stops and bus lanes) and simulates the movements of transit vehicles and the interactions between transit and non-transit vehicles. A diagram of MITSIM with bus operations capabilities is shown in Figure 4-7.
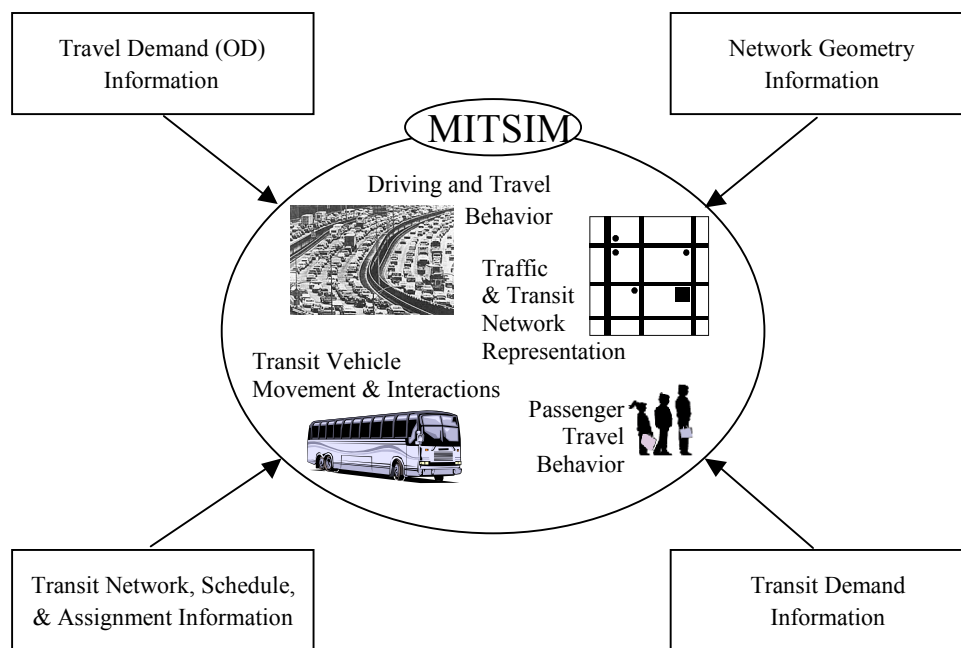
Figure 4-7: MITSIM traffic and transit inputs and models

MITSIM accepts detailed input data about the transit and traffic network, travel demand (passenger and vehicle) and bus operations and uses sophisticated behavioral models to simulate traffic and transit operations in the network. Thus, three of the modeling requirements identified in Chapter 3 are incorporated into the Transit Operations Simulator module in MITSIMLab: the *transit system representation*, *transit vehicle movement and interactions*, and the *transit demand representation*. The transit network, schedule design and fleet assignment, and passenger demand requirements are achieved through inputs to the model. However, the representation of vehicle movement and

passenger behavior is incorporated into MITSIM's internal model logic, which is the basis for bus operations simulation.

Transit System Representation

Like general network data, the components of the transit system (transit network, schedule design and fleet assignment) are generally considered to be static information from the viewpoint of traffic modeling. The makeup of the transit network, schedule and the vehicle work assignments do not change during the course of a simulation. However, these system elements provide the necessary modeling infrastructure upon which transit vehicle movements and passenger behaviors rely.

Transit Vehicle Movement and Interactions

The transit vehicle movement and interaction modeling effort in this research distinguishes bus operator behavior from the behaviors of other drivers in the network. For example, contrary to other vehicles in MITSIM, bus operator travel behavior is a function of the routes and schedules given by the user as input to the simulation rather than a simple origin-destination pair. Similarly, bus operator driving behavior includes maneuvers and decision-making processes that are unique to bus operators. For instance, bus operators may accelerate, decelerate, change lanes and perform other maneuvers in order to arrive at a bus stop, reenter the traffic stream from a bus stop, and achieve a variety of other objectives that do not pertain to other drivers.

However different the behaviors are between transit vehicle operators and other drivers, they are not independent. For example, private automobile drivers might make special lane-changing and overtaking maneuvers when traveling behind a bus in order to avoid stopping behind a bus when it reaches a stop. Thus, MITSIM as a transit operations simulator is also responsible for the interactions between buses and other modes.

MITSIM as a transit operations simulator is also responsible for simulating the interaction between transit vehicles and passengers. The most critical interaction occurs at bus stops, where passenger boarding, alighting and crowding behaviors determine the amount of time buses spend at a stop. Since bus stop level operations are such a

significant factor in determining transit vehicle progression along a route, dwell tima nd other such stop-level activity are considered a part of the transit vehicle movement and interaction requirement.

Demand Representation

A representation of passenger demand is also implemented in MITSIM to create a transit operations simulator. Passenger demand is represented as a system of inputs to the model. The behavior of passengers at bus stops is considered a part of transit vehicle movement and interaction. The time-dependent, stochastic nature of passenger arrival and distribution along a route and across the transit network are the main elements of the demand representation requirement. The parameters that describe passenger movement through the network in time and space are inputs to MITSIM's logic. MITSIM uses these input parameters to generate passengers at bus stops in the network.

4.3.2 Transit Surveillance and Monitoring

Traffic surveillance and monitoring systems are also simulated in MITSIM. Sensor devices in MITSIM, such as loop detectors, can be configured to collect a wide variety of aggregate and disaggregate traffic data, including vehicle speeds, average speeds, traffic counts, and occupancy. MITSIM is also equipped to represent vehicle-to-roadside communications, where communications devices installed along the side of the road collect information from passing probe vehicles. The representation of sensor devices in MITSIM is generic and flexible to allow the user to customize the simulated surveillance system to a particular application. Surveillance data may be collected and written to an output file for post-processing, or may be sent to TMS as input to real-time traffic management strategies.

The goal for adapting MITSIM surveillance data collection for transit operations is to enable MITSIM to reproduce the kinds of information that transit service providers collect, store, and apply in real-time through the use of APTS. Such a representation of real-time transit performance data satisfies, in part, the *APTS representation* requirement, which is also meant to include other online APTS technologies, including those that apply real-time surveillance data to operations control and those that use real-time data to

generate traveler information. Some of the APTS technologies used to produce real-time surveillance data include automatic vehicle location and automatic passenger counters. The communication between MITSIM and TMS can be used to mimic the transmission of vehicle location and passenger load information between vehicles and a transit operations control center. Likewise, sensor devices and vehicle-to-roadside communications in MITSIM may be used to mimic the sharing of location, load and other information between vehicles and field-installed devices.

Transit surveillance and monitoring systems are considerably more sophisticated than traditional traffic detection and sensing technologies. Automated vehicle location and monitoring, illustrated in Figure 4-8, is an example of these types of transit surveillance systems.
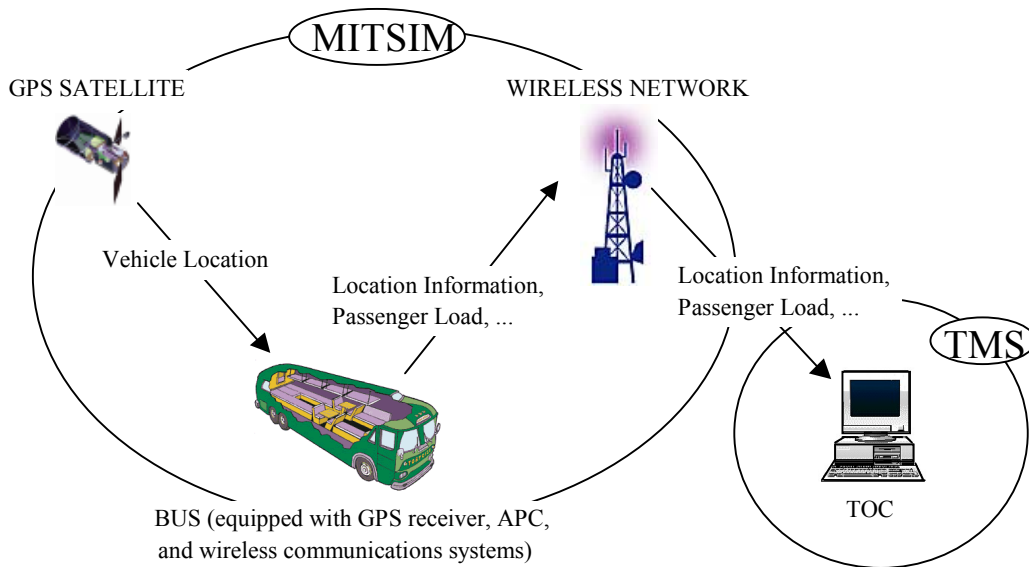
Figure 4-8: An example illustration of AVL surveillance systems

In Figure 4-8, GPS technology is used to collect vehicle location information, on-board APC systems are used to collect passenger load information, and a wireless network is used to transmit this information to the TOC.

The arrow between the communications tower and the TOC in Figure 4-8 is analogous to the link between MITSIM and TMS. With transit surveillance capabilities, MITSIM generates transit performance data and sends the data to TMS, which then mimics the application of that data at the TOC to devise strategies for improving service

in real-time. Figure 4-8 is an example of one type of transit surveillance system. However, it can be seen that transit systems monitoring relies to a great extent on an array of technologies internal and external to the vehicle, which might include communications, GPS, APC and electronic payment systems that generate important information about the vehicle's performance. This information, then, may be shared with stationary road-side installations, such as signposts, or directly with a TOC. MITSIM indirectly simulates the performance of the underlying communications and location technologies by representing the availability of transit performance data when and where it is available in the real world.

4.3.3 Transit Operations Control Center

Transit operations control center activity, like other TOC activities, is simulated in TMS. TMS mimics the logic behind the control and routing devices in the MITSIM network, and may receive real-time traffic and transit data from MITSIM's surveillance system as input to the logic of the system under evaluation. The transit operations control center is that portion of TMS that is dedicated to handling incoming transit surveillance data and executing APTS operations that take place in a TOC. Thus, the TOC operations in TMS satisfy the *APTS representation* model requirement by allowing a range of TOC operations from surveillance data collection to the use of real-time information for transit control strategies and for generating and providing traveler information to transit passengers.

APTS make possible a wide range of operations control strategies that are executed by dispatchers in the TOC. TOC strategies often include a variety of service restoration measures, which are facilitated via dispatcher-to-operator or street supervisor-to-operator communications. Service restoration strategies might be aided by real-time surveillance data (e.g. AVL, APC) and may also be supplemented by transit operations software, such as computer-aided dispatch, which processes incoming vehicle location data and calculates a set of service restoration measures from which a dispatcher may choose. Some of the measures that might be taken in order to restore service to a desirable headway or to help operators to meet scheduled arrival times or transfer connections are illustrated in Figure 4-9.
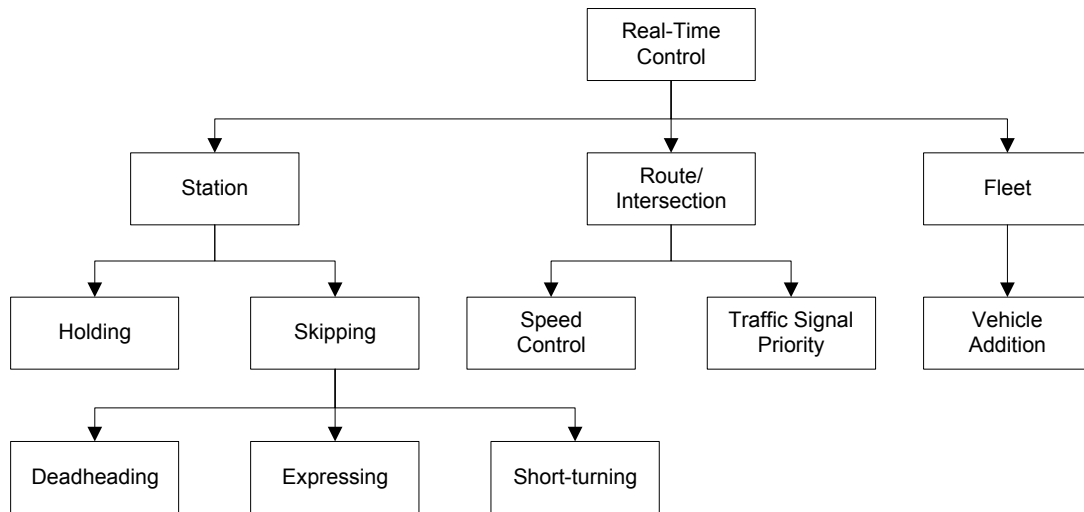
Figure 4-9: Real-time operations control strategies (source: Eberlein, 1995)

Figure 4-9 classifies real-time operations control strategies into station-based, route/intersection-based, and fleet-based strategies. Station-based strategies include holding a vehicle, typically because it is ahead of schedule or too close to the vehicle ahead, at a stop for a given interval or skipping stops to allow a vehicle that is behind schedule or too far behind the vehicle ahead to "catch up". Skipping stops can be done one of three ways: deadheading, expressing or short-turning (see Appendix A for definitions). Between stops, a vehicle that is late or ahead of schedule may be hurried along or slowed down, respectively, by controlling the vehicle's speed or by granting priority at one or more signals. Finally, fleet-based decisions may be made to restore service, such as dispatching an extra vehicle to fill a gap in service.

An illustration of how TOC control of vehicle operations is manifested within MITSIMLab's framework is given in Figure 4-10. Figure 4-10 is a modified version of Figure 4-8, illustrating the two-way communication between vehicles in the network and dispatchers at the TOC. Not all management strategies require the intervention of a TOC. Strategies that rely on communications directly between transit vehicles and field-installed control devices, such as in the case of bus signal priority, are simulated in MITSIM, and are discussed in the following section.

Figure 4-10 demonstrates through an example the way dispatchers at the TOC receive real-time performance data from vehicles in the network and communicate with operators. Communication with operators might include dispatching instructions, such as

76
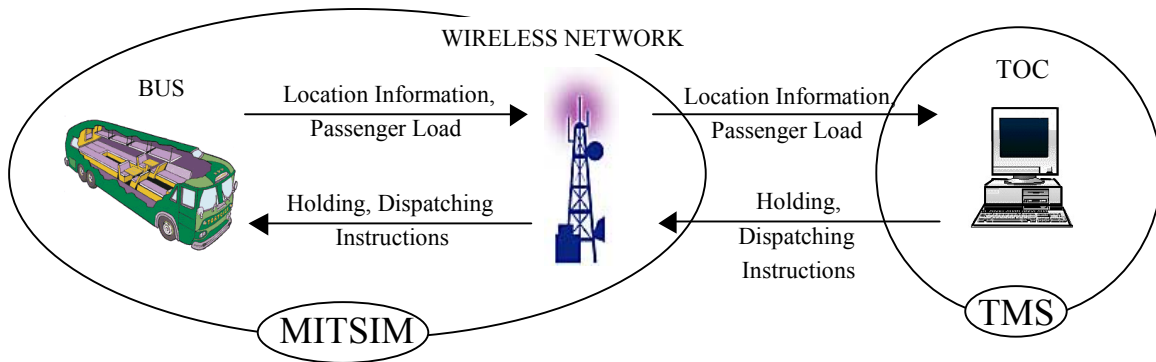
Figure 4-10: An illustration of MITSIM-TMS and bus-TOC interaction

holding, expressing and rerouting, generated by CAD software installed at the TOC. Dispatchers at the TOC may also directly manage the control system in the network by modifying traffic signal and transit priority parameters in response to prevailing traffic conditions and transit performance information. Thus, APTS strategies that are installed in the TOC would be modeled in TMS. In this way, MITSIMLab allows the user to simulate the activity of a transit operations control center through a flexible framework for testing transit control strategies.

4.3.4 Transit Control and Information Dissemination

The state of the control and information devices in MITSIMLab is simulated in MITSIM according to the logic simulated in TMS. Once TMS has evaluated the incoming surveillance data from MITSIM and has made subsequent adjustments according to the management system strategy, corresponding instructions are sent to MITSIM regarding the changes that are to be made to the control and routing information that is provided to drivers. Thus, the simulation of transit control and information provision in MITSIM partly satisfies the *APTS representation* requirement by incorporating transit control capability and information provision functionality.

MITSIM is able to represent a wide variety of traffic control and information devices. Traffic control measures such as ramp metering and pre-timed and actuated signalized intersection control are modeled in TMS. MITSIM displays the signal indication (e.g. red, green, etc.) according to information received from TMS. Likewise,

MITSIM is able to represent a number of information dissemination technologies for providing route guidance to drivers. These information technologies include, for example, in-vehicle equipment and variable message signs. TMS computes the appropriate information to be given to drivers according to the system under evaluation and delivers the results to MITSIM.

The real-time control and traveler information dissemination aspects of the APTS representation model requirement offer new challenges to MITSIM's representation of traffic control and information dissemination. Transit performance data, which MITSIM generates as it moves transit vehicles through the network, is useful for in-terminal/wayside and in-vehicle transit information systems that provide transit performance data (e.g. expected arrival time) to passengers in order to aid their trip-making decisions. Route guidance and other traveler information systems, for both drivers and transit passengers, are generally managed from a central location, such as a TOC, that monitors the prevailing traffic conditions in real-time. However, some APTS strategies do not require a TOC, but involve direct, short-range communication between the vehicle and technologies or personnel (e.g. route supervisors) located in the field. Some transit signal priority applications are an example of this kind of TOC-independent control. Figure 4-11 illustrates a hypothetical system.
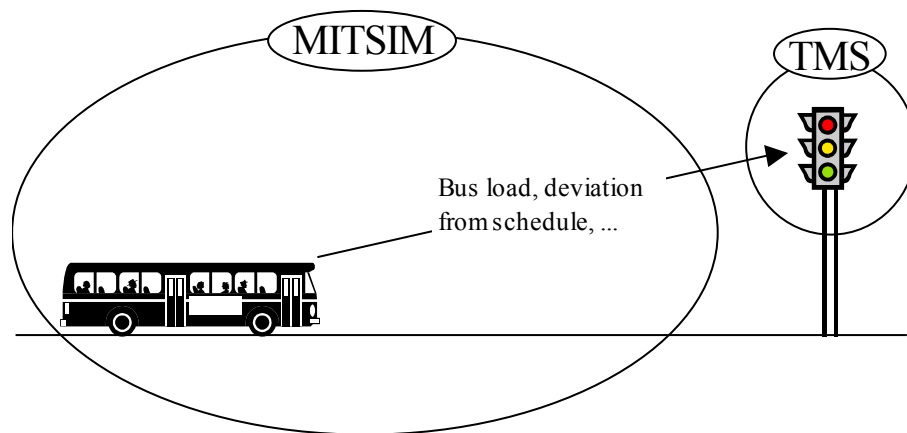
Figure 4-11: An illustration of MITSIM-TMS and bus-controller interaction

All traffic management strategies, whether through a TOC or not, however, are under the jurisdiction of TMS. In the example shown in Figure 4-11, for example, MITSIM simulates the bus' approach to the intersection and the communication of the relevant

bus-specific data to the controller (i.e. TMS). MITSIM sends the bus data to TMS, effectively alerting the controller that a bus has been detected on the approach, thus triggering the bus priority logic in TMS' generic controller.

In this chapter, the general framework for incorporating the bus transit modeling requirements identified in Chapter 3 into MITSIMLab has been discussed. In Chapter 5, the detailed implementation of the models in MITSIMLab is described.

Chapter 5

Bus Transit Modeling Implementation

The modeling requirements for simulating APTS operations in a microscopic traffic simulation laboratory are incorporated into MITSIMLab. This chapter describes the inputs, models and outputs that were implemented in order to fulfill the modeling requirements set forth in Chapter 3. To summarize, requirements for modeling and evaluating APTS in a simulation framework were organized into the following categories:

- Transit System Representation
- Transit Vehicle Movement and Interaction
- Transit Demand Representation
- APTS Representation
- Measures of Effectiveness

This chapter discusses how input files may be used to construct a detailed, realistic representation of bus transit systems by defining the transit network, schedule design, vehicle assignments and passenger demand. Furthermore, this chapter considers methods available in the literature for modeling the behavioral and operational elements of the requirements, such as vehicle movement, multimodal interaction and passenger behavior, and describes how those elements are implemented in MITSIMLab's internal simulation logic. Finally, the implementation of an APTS representation and the generation of output data for bus transit operations and APTS evaluation are described.

5.1   Transit System Representation

Bus transit system design, considered in this thesis to be a combination of the transit network, schedule and fleet assignment, is the outcome of service provider planning. A variety of APTS are designed to improve, in one way or another, the transit planning process. For example, some transit operations software, AVL data collection applications, and automated service coordination efforts help service providers to better manage and design their route structures, schedules and fleet assignments. The use of APTS for planning applications is outside the scope of operations-based traffic simulation laboratories like MITSIMLab, but the outputs of such APTS planning applications can provide useful input to MITSIMLab for evaluating various candidate route structures, schedule designs and fleet assignments.

Bus transit system design, to a large extent, dictates how efficiently, productively and seamlessly systems operate in the real world. Likewise, in a simulation model, the representation of bus transit systems is the foundation upon which transit vehicle movement and passenger behavior models rely. Therefore, in order to derive meaningful conclusions from the simulation of various service designs, and from the simulation of real-time, operational APTS as well, a large part of the modeling effort in this research is dedicated to developing a highly detailed representation of routes and schedules in MITSIMLab such that transit and traffic operations in the simulated network are sensitive to the variation in the route and schedule inputs that the user may provide.

Two main objectives were considered when designing the transit system representation input for MITSIMLab: maintaining a high degree of flexibility in terms of the types of service that may be simulated and minimizing the quantity of input data the user must generate. Following these two principles, the transit system representation requirement was fulfilled through a system of input files:

- Transit Network – the transit network representation file
- Schedule Design – the schedule definition file
- Fleet assignment – the run definition and bus assignment files

It was also necessary to make changes to preexisting input files, such as the demand input file (i.e. O-D matrix) and the network representation file. In order to understand how

each of the input files are used and how the input data are organized within MITSIMLab, let us begin with a general overview of the data objects that are created when each of the input files are read, and how those data objects are related.

Transit Network Representation

The transit network representation input file describes the pieces of a transit network that overlay the original network, including bus stops and road segments that are used by transit routes. When the transit network representation file is read, route data objects are created. Routes have unique ID numbers and have associated with them a list of links that make up their paths and a list of bus stops along their paths.

Schedule Definition

The schedule definition file describes individual trips on a route that a bus might travel. When the schedule definition file is read, trip data objects are instantiated. Trip objects have unique ID numbers, are assigned to only one route, and are given a series of scheduled arrival times at the bus stops along that route. Since some bus routes are frequent (e.g. bus rapid transit) and thus have no specified arrival times, a trip may have no arrival times. Also, since some buses may travel express along a given route (i.e. stop at only a select few stops on the route), a trip may also be assigned a subset of stops on the route. If a trip is assigned a list of stops, buses that serve the schedule will only stop at the bus stops that belong to that trip.

Run Definition

The run definition file defines the series of trips to which a single bus may be assigned. When the run definition file is read, run data objects are created. A run has a unique ID and a list of trip IDs that correspond to the sequence of trips to which the bus is assigned. A bus that is assigned a given trip "knows" its path through the network because each trip is assigned a unique route ID to which it corresponds. The series of trips to which a bus is assigned must all be connected. In other words, the end node of one trip must be the start node of the next trip in the run.

Bus Assignment

The bus assignment file defines the run to which each bus in the fleet is assigned, the type of each bus (e.g. articulated), and the start time at which the bus enters the

network. When the bus assignment file is read, bus assignment data objects are created. A bus assignment has a unique ID that is identical to the vehicle's unique ID. Thus, the bus ID is the constant link between the vehicle and it's assignment. The bus assignment object stores the bus (vehicle) ID, the bus type, the run to which it is assigned, and a number of variables that track the vehicle's progress with respect to its assignment, such as the current trip, the next scheduled arrival time, passenger load, and schedule deviation at the last stop. Unlike the other input files listed above, the bus assignment file is continuously read throughout the simulation, as long as there are assignments in the file that are yet to enter the network.

To get a better idea of how the various pieces of the transit system are organized, Figure 5-1 illustrates the relationships between the various data objects.
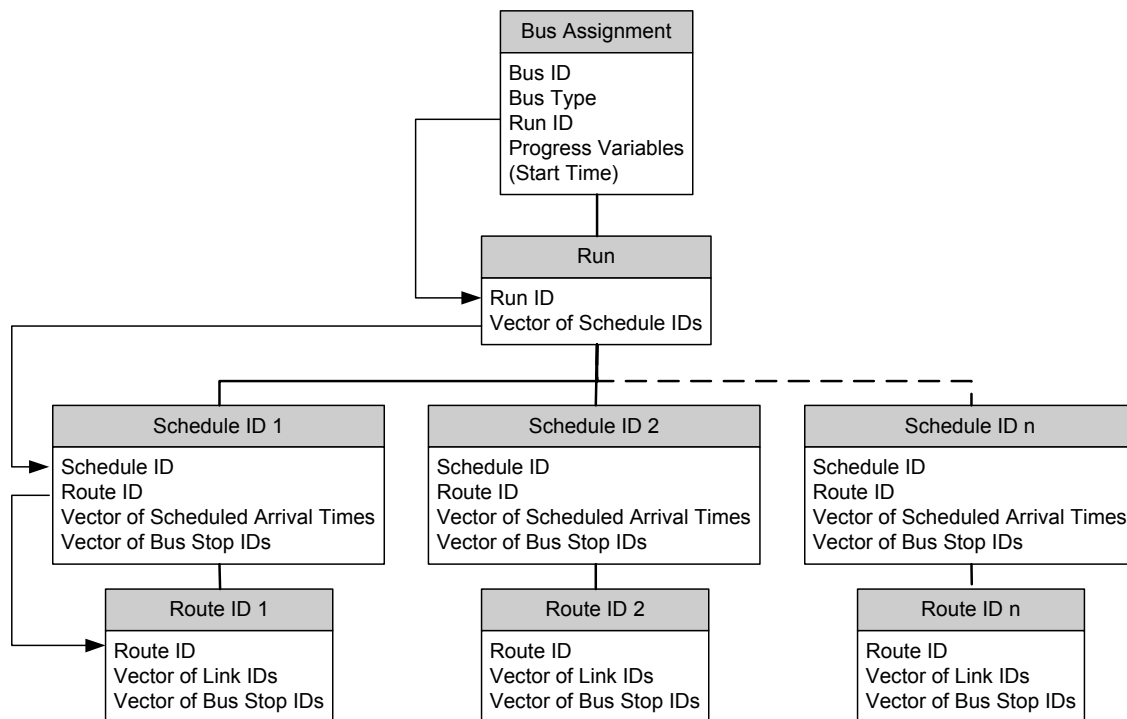
Figure 5-1: The relationships between various components of the transit system

As Figure 5-1 demonstrates, a bus assignment joins a single bus to a single run by a common, unique run ID. A run, however, is made up of a vector of one or more trips. In turn, a trip is one-way service of a single route, joined to it by a unique route ID. This

overall representation is consistent with transit practice, where vehicle runs are constructed from "blocks" of work within the schedule timetable.

Sections 5.1.1-5.1.5 below describe the input files that define bus transit supply in MITSIMLab. The changes to the original input network file are relevant to the transit network representation, and so are discussed in Section 5.1.1. Likewise, the changes to MITISMLab's original demand input file are relevant to the assignment of buses to their work tasks, and thus are discussed in Section 5.1.4.

5.1.1 Transit Network

The transit network representation file defines the portion of the road network that is used by the bus service, including the paths, or routes, followed by buses through the network and the bus stops that are located along those routes. MITSIMLab uses a path data object, which is defined by a unique ID, an origin, a destination and a sequence of links between the origin and destination, to define paths through the network to which drivers may be assigned. Route data objects, however, are quite different from paths. For instance, the endpoint nodes of a route are not defined as origins and destinations, because a route is often only a piece of a bus' total work assignment. Route objects are assigned a unique ID, and are defined by a sequence of links and a sequence of bus stops.

Figure 5-2 illustrates the way a bus route is defined in the transit network input file. In Figure 5-2, an entire bus route from terminal to terminal is included. However, the user may only want to simulate a portion of a route, or the user may want to simulate buses that serve one route for a period of time, and then interline to another route. Therefore, to allow the greatest amount of flexibility, a route object may be defined as a sequence of links and bus stops in one direction on a portion of a route, the total sequence of links and bus stops in one direction from one terminus to the other on a single route, or the sequence of links and bus stops on a complete roundtrip on a route from, and returning to, the same terminal. Furthermore, a route object may have many bus stops or no bus stops at all. Thus, the user may define interlining "routes", or paths, which do not have stops, that a bus may take from the endpoint of one route to the endpoint of another route in order to complete a work assignment on the first route and begin a new assignment on the second.

84

With such a system for defining the transit network, the user also has flexibility with regard to the size of the network and the time span to be simulated. The user may define the boundaries of the network to include any sub-portion of a route, an entire route from one terminal to the other, or the full path of a bus, including a trip from the depot to the beginning terminal of the first route, roundtrip service of several routes, interlining trips between those routes, and a return trip to the depot.


```
...
{
{ 86   # Route ID: 86, Southbound
      { 223  224  225  226  227  228  229  230  231  232  233 }  # Link IDs
      { 10  11  12  13  14  15 }                                 # Bus Stop IDs
}
{
{ 93   # Route ID: 93, Northbound
      { 471  472  473  474  475  476  477  478  479  480  481 }  # Link IDs
      { 15  16  17  18  19  10 }                                 # Bus Stop IDs
}
...
```
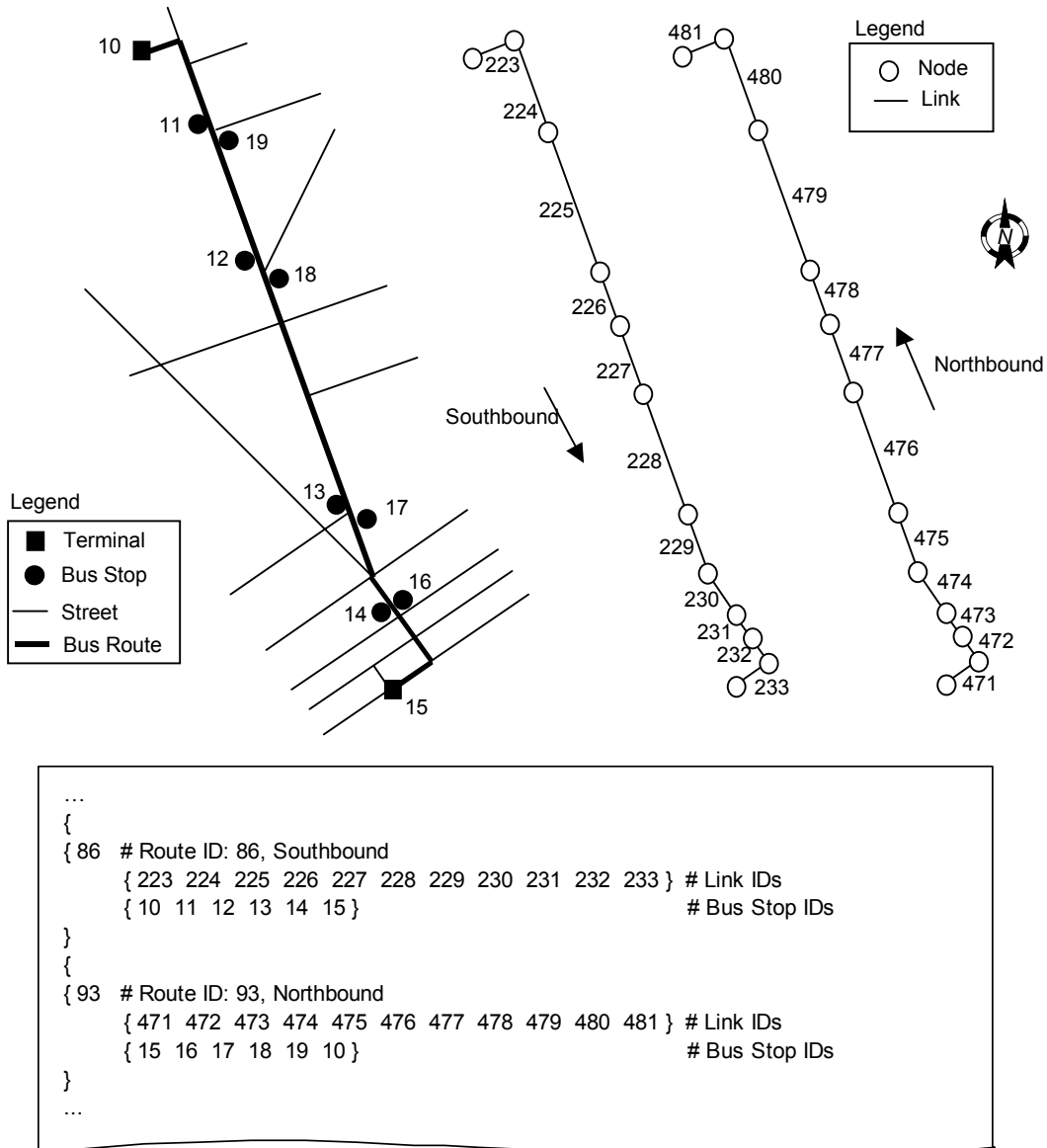
Figure 5-2: The definition of bus routes in the transit network representation input file

The user may also assign other attributes to a route that describe the service. For example, the user may include a design headway in the transit network input file. This design headway may useful when simulating strategies that aim to maintain or restore a desired headway. A sample transit network representation file is given in Appendix B.1.

The locations of bus stops in the network, along with certain attributes of bus stops, are specified in MITSIMLab's general network file, which is used to define the links and nodes that make up the network and the locations of sensors, signals and other network components. In the general network input file, the user may define the distance at which the bus stop is visible, the segment and lane in which it resides, the unique bus stop ID, the length of the stop (e.g. for multiple berths) and a wayside dummy variable that identifies whether or not the bus stop is fully removed from the general traffic stream in an adjacent bay. The length of the bus stop is particularly important to bus operations. If a bus is stopped within the length of the bus stop, but may not completely pull into the stop for any reason (e.g. congestion, another bus is already at the stop, etc.), the operator may serve passengers and proceed without stopping twice. The significance of the length of the bus stop is discussed further in section 5.2. The portion of a sample general network file that defines the bus stops is also provided in Appendix B.1.

Furthermore, lane use rules for all lanes in the network are defined in the general network input file. Thus, in the general network input file, the user may specify which lanes are HOV lanes and which are bus lanes.

5.1.2 Schedule Design

The transit schedule in MITSIMLab is represented by a table of scheduled arrival times on routes in the network, partitioned into trips, which, when joined together, make up total start-to-finish runs to which buses may be assigned. Figure 5-3 demonstrates the translation of a real-world schedule to MITSIMLab trips. The schedule shown in Figure 5-2 corresponds to the routes shown in Figure 5-3. In Figure 5-3, the real world route 9, or Cross Town route, is represented in MITSIMLab by two routes, route 86 (southbound) and route 93 (northbound). Figure 5-3 shows the portion of the schedule input file that defines the highlighted portion of the "real" Cross Town schedule.

The definitions of the routes and trips should be consistent. For example, MITSIMLab route 86 is defined by the southbound sequence of links and bus stops between terminals 10 and 15. Thus, the sequence of arrival times in the schedule input file should correspond to the sequence of stops on the route. However, if the trip serves all bus stops on the route, then the vector of bus stop IDs in the schedule input file is optional. If there are no stop IDs specified in the schedule input file, then the stops that the bus will serve are, by default, those that belong to the corresponding route object. This flexibility allows the user to define trips that serve only a subset of the stops on the route (e.g. express routes). In this case, the stop IDs must be listed in the schedule file, and the scheduled arrival times should correspond to that subset of stops.

ROUTE 9	CROSS TOWN										
	Southbound						Northbound				
	10	11	12	13	14	15	15	16	17	18	19	10
AM							6:15	6:27	6:42	6:47	6:57	7:15
							6:45	6:57	7:12	7:17	7:27	7:45
	6:00	6:35	6:45	6:50	7:03	7:15	7:15	7:27	7:42	7:47	7:57	8:15
	6:50	7:05	7:15	7:20	7:33	7:45	7:45	7:57	8:12	8:17	8:27	8:45
	7:20	7:35	7:45	7:50	8:03	8:15	8:15	8:27	8:42	8:47	8:57	9:15
	7:50	8:05	8:15	8:20	8:33	8:45	8:45	8:57	9:12	9:17	9:27	9:45
	8:20	8:35	8:45	8:50	9:03	9:15	9:15	9:27	9:42	9:47	9:57	10:15
	8:50	9:05	9:15	9:20	9:33	9:45	9:45	9:57	10:12	10:17	10:27	10:45
	9:20	9:35	9:45	9:50	10:03	10:15	10:15	10:27	10:42	10:47	10:57	11:15
	10:20	10:35	10:45	10:50	11:03	11:15	11:15	11:27	11:42	11:47	11:57	12:15
	11:20	11:35	11:45	11:50	12:03	12:15	12:15	12:27	12:42	12:47	12:57	1:15

```
...
{
{ 86    # Route ID: 86
  186 { 00:06:00  00:06:35  00:06:45  00:06:50  00:07:03  00:07:15 } # Schedule ID: 186
  286 { 00:06:50  00:07:05  00:07:15  00:07:20  00:07:33  00:07:45 } # Schedule ID: 286
  386 { 00:07:20  00:07:35  00:07:45  00:07:50  00:08:03  00:08:15 } # Schedule ID: 386
  486 { 00:07:50  00:08:05  00:08:15  00:08:20  00:08:33  00:08:45 } # Schedule ID: 486
  586 { 00:08:20  00:08:35  00:08:45  00:08:50  00:09:03  00:09:15 } # Schedule ID: 586

      ...
      { 10  11  12  13  14  15 }                              # Bus Stop IDs
}
...
```

Figure 5-3: Transit schedule representation in MITSIMLab

The scheduled arrival times are also optional. Thus, the user may define frequent bus services that have no specified arrival times, but rather a design headway. The value of the design headway, as was mentioned above in Section 5.1.1, is specified in the transit network representation file as an attribute of the route. A sample schedule definition input file is given in Appendix B.2.

5.1.3 Fleet Assignment

The representation of fleet assignment, the matching of individual vehicles with work assignments, is achieved through the use of two input files: the run definition file and the bus assignment file.

Run Definition File

Bus runs in MITSIMLab are the sequence of trips, or MITSIMLab schedules, to which buses may be assigned. A feasible run for the example in Figures 5-1, 5-2 and 5-3 is illustrated in Figure 5-4.

| ROUTE | 9 | RIO GRANDE | | | | | | | | | | |

	Southbound						Northbound					
	10	11	12	13	14	15	15	16	17	18	19	10
Trip 186							6:15	6:27	6:42	6:47	6:57	7:15
							6:45	6:57	7:12	7:17	7:27	7:45
	6:00	**6:35**	**6:45**	**6:50**	**7:03**	**7:15**	**7:15**	**7:27**	**7:42**	**7:47**	**7:57**	**8:15**
AM	6:50	7:05	7:15	7:20	7:33	7:45	7:45	7:57	8:12	8:17	8:27	8:45
	7:20	7:35	7:45	7:50	8:03	8:15	8:15	8:27	8:42	8:47	8:57	9:15
	7:50	8:05	8:15	8:20	8:33	8:45	8:45	8:57	9:12	9:17	9:27	9:45
	8:20	**8:35**	**8:45**	**8:50**	**9:03**	**9:15**	**9:15**	**9:27**	**9:42**	**9:47**	**9:57**	**10:15**
	8:50	9:05	9:15	9:20	9:33	9:45	9:45	9:57	10:12	10:17	10:27	10:45
Trip 586	9:20	9:35	9:45	9:50	10:03	10:15	10:15	10:27	10:42	10:47	10:57	11:15
	10:20	**10:35**	**10:45**	**10:50**	**11:03**	**11:15**	**11:15**	**11:27**	**11:42**	**11:47**	**11:57**	**12:15**
	11:20	11:35	11:45	11:50	12:03	12:15	12:15	12:27	12:42	12:47	12:57	1:15

Trip 393
Trip 793
Trip 1093
Trip 886

```
...
{
{ 13    # Run ID: 13
     { 186  393  586  793  886  1093 } # Schedule IDs
}
...
```

Figure 5-4: Bus run representation in MITSIMLab

According to the schedule in Figure 5-4, a bus might be assigned a sequence of alternating southbound and northbound trips. Figure 5-4 demonstrates how such a run might be constructed in the run definition input file. A sample run definition input file is given in Appendix B.3.

It is important to note the distinction between runs defined in MITSIMLab and runs defined in transit practice. Runs in transit practice usually refer to the sequence of scheduled work tasks to which a vehicle *operator* is assigned. Bus runs in MITSIMLab are loosely defined as the sequence of trips, as they are defined in the schedule definition file, assigned to a single *vehicle*. The user may define routes, trips and runs any number of ways. However, the implementation is intended to be compatible with routine transit scheduling practice, whereby scheduled trips are pieced together, in a process called "blocking", to form blocks, which are the sequence of trips to which a single *vehicle* is assigned. In a process called "run-cutting", vehicle operators are assigned to one or more blocks.

The definition of bus runs in MITSIMLab is also dependent on the physical size and boundaries of a given simulation network. If the entire extent of one or more routes is defined (i.e. terminal to terminal), then bus runs may be defined, through a sequence of inbound, outbound and interlining trips, as continuous round-trip service of one or more routes. If this is the case, then the simulation may capture all of the events that affect vehicle progression throughout its run. Conversely, if only a portion of a route is modeled in the study network, then a bus run is merely defined as the sequence of MITSIMLab trips between the entry and exit nodes. In this latter case, MITSIMLab cannot simulate events that occur outside the boundaries of the network, nor can it simulate the same bus' reentry to the network on the "return" trip on the route. Such a definition of bus runs implicitly assumes that a bus' exit time at the boundary of the network is independent of the same bus' entry time in the opposite direction at the boundary of the network, when in fact delays in one direction along a route affect the arrival time at the terminal and thus the progression in the opposite direction. However, one might assume that sufficient recovery time at the terminal is built into the schedule such that a bus will always depart from the terminal on time. It is important to consider these issues when using MITSIMLab to simulate any bus network.

Bus Assignment File

Bus assignments pair a bus with a run and define the start time in the simulation at which the bus enters the network and begins serving the trips in the run. There are two input files that may be used to assign buses to bus runs. First, individual buses may be assigned to a single run with a specified start time in the bus assignment input file. This first option is well suited for less frequent services, where the entry time into the network is more or less predictable. Assigning each bus' entry time is an important issue with respect to the boundaries of the simulated network. When both endpoints are modeled, start times are generally quite predictable, since transit service providers often include layover, or recovery, time at the terminal in the formulation of the schedule to guarantee that the vehicle departs on time. Furthermore, if the endpoints of the route are not included in the study area, then it is not only difficult to specify an entry time, but it is also difficult for the model to capture how a late arrival at a terminal, and other activity that occurs outside the boundaries of the network, affect the progression of the vehicle on the return trip. A sample bus assignment input file is shown in Appendix B.4.

However, assigning individual buses to individual runs may become tedious and redundant when the buses travel on a frequent service without scheduled arrival times. Since there are no scheduled arrival times with frequent services, there is nothing to distinguish one bus run in the service from another. Thus, all buses that serve the route may be assigned the same run ID. Furthermore, when frequency becomes high, the entry times of buses in the network become less regular and less predictable. To define a separate entry time for each assignment in the service, then, is not only cumbersome, but also unrealistic. Therefore, a second option exists that is designed to allow the user to assign buses to frequent services such as Bus Rapid Transit (BRT). The user may specify an origin-destination flow for buses in MITSIMLab's O-D demand matrix input file. Declaring bus assignments this way, the user may specify an average hourly flow rate that is the inverse of the design time headway. The user may also specify the type (e.g. articulated) of bus, the run to which the buses are assigned, and a variance and distribution that describe the probabilistic time headways between subsequent entries to the network at the specified mean flow rate. An example O-D file that contains bus assignments to frequent services is also shown in Appendix B.4.

5.2 Transit Vehicle Movement and Interactions

Vehicle movement refers to the way transit vehicle operators travel about the routes defined in the transit system input files described above and the way other vehicles behave in the presence of buses. In general, a distinction between bus operator behavior and other drivers' behaviors in MITSIMLab is sought because bus operators do not have the same trip purposes as other drivers. For instance, it is generally assumed that private auto drivers aim to minimize their travel time between an origin and a destination. On the contrary, bus operators travel with the objective of serving their assigned routes and schedules. Thus, bus operators engage in certain behavioral processes that other drivers do not. For example, buses must be in the correct lane upon the approach to a stop. Other bus-specific behavioral models, such as dwell time at a stop, are also identified as important components of vehicle movement modeling.

This modeling effort also addresses the interactions between buses and other vehicles in the network in order to capture the impacts of each mode on the other, and thus to achieve a truly multimodal simulator. This discussion considers two behavioral regimes: behavior at and near bus stops and behavior between stops.

There has been very little research dedicated to modeling transit vehicle movements and interactions with other vehicles to support the modeling effort in this research. While bus characteristics, such as size and acceleration/deceleration capability, are represented in microscopic traffic simulation models, it has been assumed implicitly that bus operators accelerate, merge and change lanes according to the same decision-making processes as other drivers. Likewise, it has been assumed implicitly that private automobile drivers behave no differently in the presence of buses than in the presence of other vehicle types. Aside from stopping and starting at bus stops, there has traditionally been little or no behavioral distinction between bus operators and other drivers (Silva, 2001). Most transit modeling in the literature is largely dedicated to bus stop operations, such as dwell time modeling. Thus, in sections 5.2.1 and 5.2.2 below, what limited experience is available in the literature is considered in the implementation.

5.2.1 Behavior Between Stops

Recalling the definition adopted earlier in Chapter 3, vehicle movements between stops refers to driving behaviors that control the vehicle's trajectory from one stop to the next, after it has pulled out of a stop and before it begins to pull into the next stop. The types of behavior that occur between stops can generally be summarized by lane-changing and accelerating behavior. Also recalling from Chapter 3, acceleration behavior is assumed to be identical to the acceleration behavior of other drivers. The modeling effort with regard to behavior between stops, then, is focused on lane-changing.

The lane-changing behaviors considered here include both bus operators and private automobile drivers. Let us first consider bus operator lane-changing. Three important issues were raised in Chapter 3 with respect to bus operator lane-changing behavior. These are:

- Mandatory lane-changing to arrive at bus stops
- Discretionary lane-changing when the bus is far from the downstream stop
- Lane choice when bus lanes are present

The first two items in the list above rely on whether or not a bus stop exists downstream and is sufficiently close that it influences the operator's behavior. It may be assumed that bus operators generally know their routes very well and are familiar with the network. In order to reflect this assertion, three changes were made in MITSIMLab with respect to driver characteristic parameters.

Bus Operator Characteristics

The first parameter is the driver's "look-ahead" distance. Drivers in MITSIMLab whom are assigned habitual paths have a look-ahead distance, which is probabilistically distributed between some lower and upper limit. In many microscopic traffic simulators, drivers are only aware of the conditions on their current link, and thus may not make lane-changing decisions far enough in advance and therefore cause unnecessary congestion when the driver must make a sudden lane change maneuver in order to reach a turn or exit. The look-ahead feature in MITSIMLab allows all drivers to consider the entire distance downstream within their look-ahead distance, irrespective of link

endpoints. The look-ahead distance may vary from driver to driver to reflect the variability in familiarity with the network that exists in the driving population. Since it is assumed that bus operators know the network very well, buses are automatically assigned the maximum value for the look-ahead distance.

Second, there exists in MITSIMLab a driver attribute called "familiarity". The familiarity attribute affects the driver's visibility, which affects the amount of time and distance within which a driver may react to downstream signs, signals and events. Driver visibility varies from driver to driver in MITSIMLab to reflect the variability among the population of drivers, but the familiarity attribute is used to identify special cases where drivers are so acutely aware of (i.e. familiar with) their surroundings that their visibility is especially high. The familiarity attribute is binary. In other words, drivers are either "familiar" with the network or not. The visibility of drivers that are "familiar" with the network is doubled. "Familiar" drivers thus rely not only on the physical limitations of eyesight, but on a knowledge of the network. It is assumed that bus operators are among these drivers, and are thus declared to be "familiar" with the network.

Lastly, it is assumed that bus operators begin making special lane-changing decisions far in advance of bus stops to ensure that the bus arrives at a downstream stop. Therefore, an input parameter was created that allows the user to input the distance in advance of a stop at which the driver begins to consider lane-changing maneuvers in order to reach the lane where the stop resides. This parameter, termed the bus-to-stop visibility, is especially important in simulated urban networks that are very congested and thus cause buses to "inadvertently" skip their stops because they do not make the appropriate maneuvers far enough in advance.

Mandatory Lane-Changing to Arrive at Stops

MITSIMLab distinguishes between mandatory and discretionary lane-changing, where mandatory lane changes are those that the driver must execute in order to meet a turn or exit that connects to his/her path or to avoid blocked lanes. Discretionary lane changes are considered when a mandatory lane change does not dictate lane-changing behavior. Drivers make discretionary lane changes in order to achieve what they perceive to be gains in travel speed. In order to avoid unrealistic cases in MITSIMLab

where a bus passes a stop without stopping because the operator is unable to change lanes in congested conditions, buses enter a mandatory lane-changing regime when a bus stop in its schedule assignment is within its bus-to-stop visibility. The bus operator will maneuver toward the lane that contains the bus stop, whether it is on the left or right hand side of the road, as soon as acceptable gaps are found. However, events, such as incidents, that occur upstream of a bus stop take precedence over bus stops, and bus operators will make the necessary lane changes in response to the event before resuming the mandatory lane changing behavior prompted by the bus stop.

Discretionary Lane-Changing Away from Stops

When the bus is sufficiently far from the next downstream stop (i.e. the bus stop is greater than the bus-to-stop visibility distance from the bus), the operator may make discretionary lane changes with a preference toward the lane that contains the bus stops. Bus operator discretionary lane-changing is determined according to the same logic that applies to other drivers. If the bus operator perceives that gains in speed may be achieved in an adjacent lane, MITSIMLab will compute the probability that the operator will choose to change lanes, and the operator will execute the maneuver provided that a satisfactory gap exists.

Lane Choice in the Presence of Bus Lanes

When bus lanes are present, buses generally use them. In order to reflect this attraction to bus lanes, bus operators in MITSIMLab, when unconstrained by events that require a mandatory lane change, will always exhibit a strong discretionary preference for the bus lane. In other words, if a bus operator ventures out of a bus lane as a result of a mandatory lane change, the operator will always make discretionary lane changes to return to the bus lane once the mandatory constraint has passed. Furthermore, when buses arrive at a signal and are making a left or right turn onto a street that contains a bus lane, the operator will always pull directly into the bus lane, provided the road geometry and conflicting movements permit.

Non-Transit Vehicle Lane-Changing

The lane-changing model for other, non-transit, drivers in MITSIMLab was also modified to incorporate Silva's postulation that drivers will prefer not to travel behind a bus in a lane that contains bus stops (Silva, 2001). In order to capture this kind of behavior, a dummy variable has been added to the utility of a lane when MITSIMLab calculates, according to a discrete lane-choice model, the probability that a driver will choose an adjacent lane. The dummy variable is equal to one if the lane change would place the vehicle directly behind a bus in a lane that contains bus stops and zero otherwise. The dummy variable thus incorporates into the model a disincentive for traveling behind a bus, which the driver purportedly anticipates will eventually be slowing and stopping at bus stops downstream. This "bus-following" dummy, when the lane-changing model is calibrated, should have a negative coefficient, which would confirm the assumption that drivers seek to avoid being delayed behind buses that periodically stop to serve passengers.

Bus Operator Route Choice

Necessary changes were also made to MITSIMLab's traveling behavioral models. For example, buses generally have fixed paths, and so bus operators do not make route choices, as do other drivers. Therefore, in order to spare unnecessary computation time and to prevent bus operators from making errant route choices that may lead them from their scheduled routes, a condition was added in MITSIMLab that reserves the route choice models for all drivers except bus operators.

5.2.2 Behavior At and Near Stops

Driver behavior at and near stops pertains to the behaviors of bus operators at bus stops and the behaviors of both bus operators and other drivers that are present when a bus is pulling into or out of a stop. Modeling of bus operator behavior at stops in the literature is largely focused on dwell time modeling. The literature review below also raises operational issues with respect to bus operator and private auto driving behavior when buses enter and pull out of bus stops. For instance, when pulling out of a wayside stop, a stop that is set apart from the general traffic lane, the bus will cause delay to the

adjacent traffic stream as it forces its way back into traffic. Simultaneously, vehicles in the adjacent traffic stream must yield to the accelerating bus in order to allow it to depart from the stop. These kinds of issues relating to driving behavior near stops are taken into account in MITSIMLab. Below, the discussion of vehicle movements at and near stops is separated into a discussion of behavior at stops and behavior near stops.

Behavior At Stops

Bus operator behavior at stops has mostly to do with dwell time operations, the time the bus operator spends stopped with the doors closed, the time the operator takes to open and close the doors, and the time it takes to serve passengers while the doors are open. Before pursuing a dwell time model implementation in MITSIMLab, relevant methods and experiences in the literature are considered.

Background and Literature

The most common and simple dwell time models assume dwell time to be a linear function of the number of boarding and alighting passengers and assume the following form:

$$T = \alpha + \beta N$$

where T is the dwell time at a given stop, N is the sum of boarding and alighting passengers at the stop, and α and β are parameters. The coefficient of the number of boarding and alighting passengers β may be interpreted as the average alighting/boarding time per passenger. The constant α is the dead time. Levinson (1983) used this same model to estimate the dwell times at bus stops in various cities in the United States (Boston, Chicago, New Haven, San Francisco). Levinson found 5.0 and 2.75 to be representative values of α and β, respectively.

Researchers have also studied nonlinear dwell time models. Given dwell time and passenger demand data for a bus route in Lafayette, Indiana, Guenthner and Sinha (1983) noticed that total dwell time increased with the number of boarding and alighting passengers, but that the dwell time per passenger decreased as the number of boarding

and alighting passengers increased. Guenthner and Sinha proposed the following nonlinear dwell time model:

$$t = 5.0 - 1.2\ln(N),$$

where t is the dwell time per passenger and N, again, is the number of boarding and alighting passengers. The modest R^2 (0.36) value for the model led Guenthner and Sinha to believe that dwell time might be a function of more than just the number of boarding and alighting passengers, including fare structure, number of doors used for boarding and alighting and fare-collection strategy.

Vandebona and Richardson (1985) studied the effects of various fare collection strategies on tram performance along a route between East Burwood and the Melbourne central business district in the U.K. The dwell time models reviewed in the study can be, and have been, applied to bus transit. Furthermore, although tram fare collection strategies in the U.K. might be different from bus fare collection in the U.S., this study is pertinent because it is conceivable that a similar study may be conducted to study the effects of different electronic fare payment technologies on bus operations. Vandebona and Richardson examined four dwell time models:

1. The Sequential Model: $T = \gamma + \alpha A + \beta B$

   where T = dwell time,

   γ = dead time,

   α = alighting time per passenger,

   A = number of alighting passengers,

   β = boarding time per passenger, and

   B = number of boarding passengers.

2. The Interaction Model: $T = \gamma + \alpha A + \beta B + \delta(AB)$

   where the term $\delta(AB)$ accounts for the interaction between the boarding and alighting passenger streams.

3. The Simultaneous Model: $T = \max\begin{bmatrix} \gamma_A + \alpha A \\ \gamma_B + \beta B \end{bmatrix}$

   where γ_A and γ_B are the dead times for the alighting and boarding doors, respectively. The simultaneous model is applicable where buses use one set of

doors for alighting passengers and another for boarding passengers. Dwell time in this case is determined by the larger of the alighting service time and the boarding service time. The different dead times allow for different door types.

4. The Multi-Rate Boarding Model: $T = \begin{cases} \gamma + \beta_1 B_i & 0 < B_i < x \\ \gamma + \beta_1 x + \beta_2 (B_i - x) & x < B_i \end{cases}$

where β_1 is the boarding rate for B_i passengers when x or fewer passengers are waiting to board, and β_2 is the boarding rate for the number of passengers in excess of x. The multi-rate boarding model allows for the boarding rate to vary with the number of boarding passengers, which might explain the increasing dwell time when crowding (e.g. standing passengers on board) occurs. The model may also be used to explain the phenomenon observed by Guenthner and Sinha, where the boarding rate per passenger decreases as the total number of boarding and alighting passengers increases.

The variety of models described above sheds light on several factors that affect the boarding and alighting rates, and thus the dwell times at stops. These factors include the number of doors, door utilization, the door opening and closing mechanisms, fare collection strategies, interactions between alighting and boarding passengers and between boarding passengers and congestion on board the vehicle.

The TRAMS simulation package used to evaluate tram operations under the different fare collection strategies also addressed the issue of vehicle capacity. In order to represent real-world behavior, the model does not strictly forbid more passengers to board than the vehicle capacity will allow. Rather, if the passengers waiting to board the tram threaten to exceed vehicle capacity by 5 or fewer passengers, all of the boarding passengers are permitted to board. This loading model prevents the case where very few passengers are left behind by a full vehicle. In reality, tram capacity in Melbourne is not strictly observed, and passengers are permitted to board in marginal excess of the intended capacity.

There are other dwell time models proposed in the literature that are worth noting. Marshall et al. (1990) estimated several different dwell time models for bus service in Manhattan, New York. Marshall et al. estimated linear models that were functions not only of the number of boarding and alighting passengers N, but also of bus-induced

delays D (e.g. due to bus-queuing, bus holding for schedule adjustments, waiting to serve straggling passengers, etc.) and whether or not the fare collection strategy accepted bills, denoted BILLS (0 if bills not accepted, 1 otherwise). Marshall et al. also estimated several exponential models of the form

$$T = \sigma N \eta \; exp(\rho_1 BILLS + \rho_2 D),$$

where σ, η, ρ_1 and ρ_2 are parameters, and determined that the exponential model had the higher R^2 value, 0.71, compared with 0.53 for a linear model that is a function of N alone.

Lin and Wilson (1992) studied several dwell time functional forms for light rail service in Boston, Massachusetts. Lin and Wilson consider several linear and nonlinear variations of a one-car train model that accounts for the congestion effect of standing passengers aboard the train:

$$T = \gamma + \alpha A + \beta B + \delta (A+B) \; (STD),$$

where STD is the number of standing passengers aboard the train. Some of the models examined in the study include:

$$T = \gamma + \alpha A + \beta B + \delta LS,$$
$$T = \gamma + \alpha A + \beta B + \delta LS^{\phi},$$

where LS is the number of departing standing passengers and ϕ is a parameter. The results of the estimation showed that the latter, nonlinear model ($R^2 = 0.65$) had a slightly stronger explanatory power than the former, linear model ($R^2 = 0.63$).

The TCQSM recommends the "sequential model", shown again below, for calculating transit capacity (Kittelson & Associates, 1999).

$$T = \gamma + \alpha A + \beta B$$

Furthermore, the TCQSM recommends values for γ, α and β based on bus type (e.g. low-floor) and design, and fare payment strategy. The TCQSM also recommends adding 0.5 seconds to the value of β when there are standing passengers on the bus to account for congestion effects.

Implementation

The literature review raises a number of issues that should be considered when modeling dwell time. Perhaps most importantly, dwell time depends on passenger demand and on the interactions between passengers as they board and alight from the bus. However, the passenger boarding and alighting behavior is a function of bus-specific characteristics. One of the recurring themes in the literature review is that of bus technology, including the number of doors on the bus, how the doors are used, fare collection strategies and technologies, and whether or not the bus has low-floor entrances. In order to account for different types of buses, and to account for the implications that each bus type may have with respect to dwell time in MITSIMLab, the user may input various parameters for any number of bus types.

The bus class categories that the user may create are analogous to the vehicle class categories in MITSIMLab, which allow the user to simulate various types of vehicles with varying sizes, acceleration and deceleration capabilities, and other vehicle characteristics. The implementation of the bus classes in MITSIMLab effectively creates a vehicle type hierarchy. The user only needs to specify one vehicle of type "bus" in the general vehicle class input table. In the bus class input table, the user may specify different bus types and the various properties that pertain only to buses. Furthermore, since buses in the same fleet may have varying dimensions (e.g. longer, articulated buses vs. shorter, non-articulated buses), the user may specify a vehicle length in the bus class that will override the bus length specified in the vehicle class table. The various bus-specific parameters that may be specified in the bus class table include:

- Length
- Seating capacity
- Total (seating + standing) capacity
- Average passenger boarding rate (e.g. 3 sec/passenger)
- Average passenger alighting rate (e.g. 2 sec/passenger)
- Dead time lower bound (sec)
- Dead time upper bound (sec)
- Crowding factor (e.g. 0.5 sec/passenger)

The dwell time modeling discussion in the literature review suggests that dwell time parameters, such as passenger boarding time, are a function of various characteristics of the bus. Thus, the input bus characteristics listed above allow the user to vary the dwell time parameters by bus type. The specification of bus types and characteristics is provided in Appendix D. Each bus' type is declared in the bus assignment input.

The default dwell time model implemented in MITSIMLab is a sequential model like that suggested in the Transit Quality of Service Manual (Kittelson & Associates, 1999),

$$T = \gamma + \alpha A + \beta B,$$

where A is the number of alighting passengers, B is the number of boarding passengers, α is an average alighting rate, β is an average boarding rate, and γ is the dead time. When the load on the bus is greater than the seating capacity (i.e. standees are present on the bus), a crowding factor is added to β to account for crowding. With this implementation of dwell time modeling in MITSIMLab, many of the phenomena that affect dwell times, like passenger crowding and increased passenger boarding rates with advanced fare collection technologies, can be captured. Furthermore, the variability in passenger and bus operator behavior that leads to dwell time variability is included. For example, the dead time at a stop is probabilistically distributed between a lower and upper bound to account for the different behaviors of bus operators.

Behavior Near Stops

For the purposes of this thesis, behavior near stops is defined as operator behavior when entering and departing from stops. The discussion in Chapter 3 identifies various operational issues relating to vehicle movements entering and leaving stops. Bus operator behavior on the approach to and departure from a stop can have significant impacts on the adjacent traffic stream. Likewise, the behaviors of other drivers in the adjacent traffic stream can severely affect bus operations. The modeling effort in MITSIMLab pays special attention to this interaction between modes near stops. Below, relevant methodologies and experiences in the literature are reviewed before choosing a modeling implementation for transit vehicle movement and interactions near stops.

Background and Literature

Behavior near stops pertains to those bus operator behaviors involved with entering and leaving stops. Buses often stop in the rightmost general traffic lane to serve customers waiting at a stop, thus fully or partially blocking the lane. However, when bus stops are located adjacent to, and separate from, the general traffic lanes, bus operators must make certain maneuvers in order to pull into and out of the stop. A bus operator maneuvering out of and back into the traffic stream to serve a bus stop can be modeled by default according to the preexisting acceleration and lane-changing models in a traffic simulation model. However, these maneuvers are more complex than general behavioral models might suggest. General acceleration, lane changing, merging and other models do not account for the interactions between the buses and the mixed traffic stream near bus stops. Hence, a lack of sophisticated representation of bus behavior entering and leaving stops might overstate bus delay when a bus is departing from a stop and/or the delay caused to other vehicles by the merging bus.

The critical bus operator maneuver near wayside bus stops is the departure from the stop. When a steady traffic stream occupies the general traffic lane into which the operator must enter, the operator must locate a gap into which it may accelerate from a standstill. General lane-changing models might not represent these conditions realistically. In most lane-changing models, the acceptable gap into which the subject vehicle will merge is a function of its position relative to the lead and lag vehicles and its speed relative to the lag vehicle in the target lane, as shown in Figure 5-5 (Ahmed, 1999).
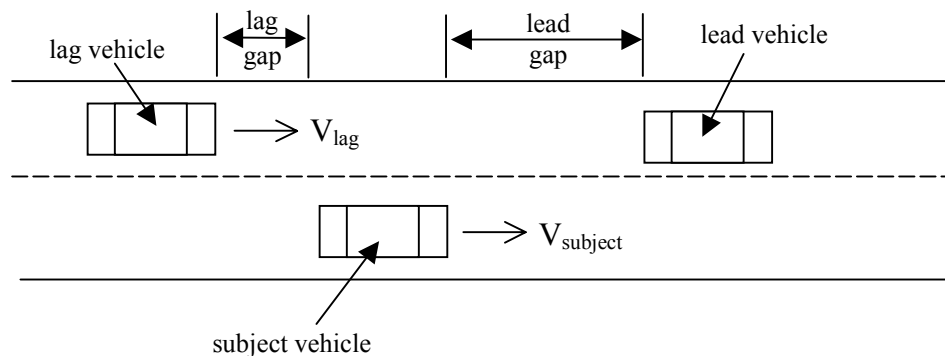
Figure 5-5: Illustration of general lane-changing logic

With a velocity of zero, the bus operator is not likely to find an adequate gap in a realistic period of time. Some lane changing models compute the probability that the lag vehicle will yield to a merging vehicle. Generally, however, a vehicle will not yield to another vehicle that has not first deemed the gap acceptable.

There is very little literature available regarding bus operator behavior near stops. However, Silva (2001) studied the effects of bus operations on mixed traffic. In order to model buses merging into general traffic lanes from bus stops, Silva used a variable to represent each driver's willingness to yield to a bus leaving a stop. Silva modeled bus operations in London, where the general rule is that buses pulling out of stops have priority over the vehicles upstream in the target lane. The driver's willingness to yield to buses leaving stops was assigned randomly to each driver in the network.

The operating procedures and policies of the service provider also govern a bus operator's behavior regarding departure from a stop. For instance, bus operators may depart once all alighting passengers have alighted and all boarding passengers have boarded, regardless of the time. On the other hand, if the bus is ahead of schedule, the bus operator might routinely wait at the stop until a scheduled departure time before leaving. Therefore, dwell time may not be the only determinant of the length of time a bus sits at a stop. The bus's departure time may be a function of operator discretion, service provider policy, and passenger demand. Furthermore, bus operators might depart according to holding and dispatching instructions received from the transit operations control center (TOC). Thus, the time a bus departs a stop may also be influenced by a combination of the APTS technologies in place and the TOC decision-making in response to APTS.

It is not apparent that operator behavior upon arrival at a stop is any more complex than general deceleration and, in the case of wayside stops, maneuvering laterally into the stop bay. Given that the bus operator is "aware" of the upcoming stop and makes the necessary lane-changing maneuvers in order to arrive at the stop, which are addressed in the discussion of behavior between stops, modeling a bus operator pulling into a stop might well be modeled according to default acceleration models, which typically calculate a safe braking distance and an appropriate applied deceleration. The critical driving behavior when a bus approaches a stop is that of the other vehicles

behind the bus in the same lane. It is important that the behavioral models not overstate the delay caused to vehicles that either decelerate dramatically while a bus maneuvers into the wayside stop bay or that decelerate and stop behind a bus that serves passengers in the rightmost lane.

Silva (2001) set out to model the tendency of private auto drivers to overtake buses when traveling behind a bus in a lane that contains stops downstream. Silva postulated that drivers know that the bus will eventually be slowing to a stop to serve passengers and thus will anticipate the bus' behavior and change lanes or "squeeze" around the bus in the same lane in order to pass the bus and avoid being delayed. Silva's model assumed that drivers following buses in a lane containing bus stops change lanes to overtake the bus as soon as an acceptable gap in the adjacent lane becomes available, and then move back into the original lane once the bus has been overtaken. This observed behavior suggests that general car-following acceleration models do not sufficiently capture the interactions between buses and other modes.

Just as bus operator behavior upon departure from a stop is a function of both driving behavior and the service provider's operating procedures, bus operations approaching the bus stop may also be governed by the service provider's operating procedures. For example, bus operators may not serve a stop unless either a passenger on board has requested the stop or the operator sees passengers waiting at the stop. In such a case, the bus operations models should reflect the observed interactions between the passengers and the bus operators.

Implementation

It was assumed in Chapter 3 that bus operator behavior when entering a stop, whether it is a wayside stop or in the general traffic lane, can be reasonably well modeled by current lane-changing and accelerations models. In MITSIMLab, a bus' approach to a bus stop is modeled similarly to a vehicle's approach to a tollbooth or red light, whereby MITSIMLab calculates a safe braking distance and a corresponding deceleration in order to stop at the appropriate location. With the inclusion of the mandatory lane change rule for arriving in the appropriate lane at a bus stop, MITSIMLab's general acceleration models are assumed to be suitable models for bus entry to a bus stop.

However, certain behaviors were included in a bus' approach to a stop to reflect realistic operations. For example, a bus may load and discharge passengers if it is stopped just upstream of a stop in congested conditions. In other words, if a bus operator is stopped very near to a stop, but unable, due to congestion, to pull up to the "stop line" at the stop, the operator may open the doors and commence service of the stop. In order to determine whether the bus is near enough to the "stop line" at the bus stop, a bus stop length may be specified in the general network input file when the stop is defined. If the entire length of the bus is within the bus stop's length, the bus may serve the passengers and continue on its route without stopping again at the "stop line" at the stop. This also allows for the simulation of multiple berth stops, where, if a bus on a different route is already stopped at a bus stop, the approaching bus may simultaneously serve the stop if the stop is long enough to accommodate two bus lengths.

Model improvements were also implemented to capture the behavior of other drivers when traveling behind a bus that is actively decelerating to enter and serve a stop. Silva (2001) observed that drivers behind buses tend to overtake the bus at the earliest opportunity, in anticipation of the bus' impending stop, to avoid delay behind the bus. This phenomenon is accounted for in MITSIMLab. The lane-changing model, as was described in Section 5.2.1, includes a disincentive for traveling behind a bus in a lane that contains bus stops. However, this bus-following disincentive does not account for wayside stops that are located in *another* lane, neither does the disincentive account for the added motivation to change lanes and overtake the bus when the bus is actively decelerating. When a driver is traveling behind a bus and the bus is in the process of decelerating to serve a stop, the driver following the bus will commence a discretionary lane change and execute the lane change as soon as an acceptable gap is available.

In the modeling effort, steps were also taken to capture the behavior of bus operators and other drivers when a bus is departing from a stop. The critical departure maneuver occurs at wayside stops. When the stop is located in the general traffic lane, the bus has no obstruction and may accelerate once the doors are closed. However, when departing from a wayside stop, the bus must find an acceptable gap and pull into the adjacent traffic stream. One may observe in the U.S. that bus operators do not wait long for vehicles to yield to them. Typically, bus operators immediately force their way into

the traffic stream, thereby forcing drivers in the adjacent lane to yield. In MITSIMLab, there are several lane-changing regimes, one of which is called forced merging. When a vehicle must make a lane change, but is unable to find an acceptable gap and is approaching the critical location before which the lane-change must be completed, the driver "noses" its way into a gap in the target lane, forcing the lag vehicle in the gap to yield. In the case of a bus departing from a stop, it is assumed that the bus operator immediately enters a forced merging regime, and noses into a gap before experiencing unrealistically excessive delays. Also, drivers upstream in the bus' target lane have a high probability of yielding to the bus.

In this section, the various vehicle movement-based modeling features that have been implemented in MITSIMLab are described. These models are meant to establish a basic representation of microscopic bus operations in a transit network and to lay the groundwork for incorporating new and more sophisticated bus and multimodal interaction behavioral models in the future. Next, the discussion in Section 5.3 focuses on the demand side of bus operations and on the implementation of a passenger demand representation in MITSIMLab.

5.3   Transit Demand Representation

Passenger demand may be modeled at various levels of detail. In the simplest case, there may be no representation of passenger demand. In this case, dwell times may be randomly generated according to some probabilistic distribution. Such a simple passenger demand representation, however, does not capture the effects of passenger interaction during boarding and alighting on dwell times from stop to stop.

At a more sophisticated level, passenger demand might be modeled using arrival rates and percentage of passenger load alighting. One can assume that passengers arrive according to some probabilistic distribution. Thus, given an average arrival rate, the model generates randomly the number of passengers waiting to board based on the vehicle headway. Likewise, the percentage of the bus load alighting at a stop will determine the number of alighting passengers. In this second case, passengers are generated numerically, but have no identifying characteristics, origins or destinations.

A third, more sophisticated representation of passenger demand involves passenger origin-destination flows. With OD flows, individual passengers may be generated as data objects with assigned attributes (e.g. age, income), origins and destinations. This way, the passenger experience (e.g. waiting time, in-vehicle time, etc.) may be tracked from the origin to the destination, and the passenger may make route choice and other decisions based on traveler information. A significant advantage of this more detailed representation of the passenger is the ability to capture the effects of traveler information, transfer connections and other aspects of the trip experience that transpire at the individual level.

According to the discussion in Chapter 3, a considerable proportion of time a bus spends in service is spent at bus stops. Furthermore, passenger demand at a given bus stop is the single most important determinant of the amount of time a bus spends at that stop to serve passengers. Since passenger demand can exhibit considerable variability spatially, at the route level, the sub-route level and at the bus stop level, as well as temporally, with peaks, off-peaks and spikes, it is regarded as a priority in this research to represent in MITSIMLab the spatial and temporal variation in passenger demand for boarding and alighting throughout a network. Since the pattern of passenger flow and distribution through a transit network is largely a function of local and regional land use characteristics and of a variety of passenger attributes, it is assumed that the nature of passenger demand for the service does not vary in real time. Thus, passenger demand information is required as input to MITSIMLab.

The input file for specifying passenger demand in a simulated transit network allows the user to vary the demand for boarding at stops by time, by route and by bus stop. Likewise, the demand for alighting at stops may be varied by time, by route and by bus stop. A portion of a sample transit demand input file is shown in Figure 5-6. This way, the user may vary the pattern of passenger distribution at the route, sub-route and stop levels, by effectively specifying trip productions and attractions for different transit origins and destinations, respectively, in the network. The parameters specified in the sample file in Figure 5-6 come into effect when the simulation time reaches the time (e.g. 00:08:00, 00:09:30, etc.) specified in the file.

```
...
00:08:00
{
  10 { 86  120  0.10 }  # Bus stop ID { Route ID  Arrival Rate (pass/hr)  Alighting Percentage }
  11 { 86  100  0.20 }
  12 { 86  150  0.35 }
  13 { 86  140  0.30 }
  ...
  16 { 30.0  70.0 }  # Bus stop ID { Dwell Time Lower Bound  Dwell Time Upper Bound }
  17 { 40.0  80.0 }
}
00:09:30
...
```

Figure 5-6: Input file for passenger demand information

Figure 5-6 demonstrates two ways to represent passenger demand to MITSIMLab. First, the user may offer an average passenger arrival rate and a percentage of the bus load alighting by stop and by route. Second, for cases where detailed arrival and alighting data is scant or unavailable, the user may enter lower and upper bounds for dwell time by stop alone. When lower and upper bounds are used, the dwell time may be drawn randomly from a uniform or other probabilistic distribution. All values are time dependent, and thus may be varied at any desired time granularity. A sample demand input file is provided in Appendix C.

In order to capture the inherent random variability in passenger demand, passengers in MITSIMLab are generated according to a Poisson distribution with an average arrival rate that is specified in the passenger demand input file. Bus stop data objects in MITSIMLab store vectors of the current values of several passenger demand parameters such as average arrival rate and alighting percentage, reserving in each vector an element for each route that serves the stop. Bus stop objects also record and store current values of several performance variables, such as the time a bus on a given route last arrived at the stop. Using this information, MITSIMLab computes the time headway between the arrival of one bus and the next on a given route at a given bus stop. Subsequently, MITSIMLab computes the number of passengers waiting to board the bus by randomizing the product of the prevailing average arrival rate and the time headway.

The number of passengers alighting at each stop is calculated as the percentage of the bus load specified in the passenger demand file for each stop and route.

The chosen aggregate level of passenger demand representation provides the basic functionality for capturing the temporal and spatial variability in passenger demand that cause, in part, various bus operations phenomena like bus bunching. Modeling of individual passengers with origins, destinations and personal attributes, and modeling of passenger route choice, is reserved for future research. Therefore, the modeling effort in this research does not provide the disaggregate representation of passenger demand that is necessary for simulating APTS that rely on passenger-based travel behaviors, such as passenger responses to traveler information systems.

5.4 APTS Representation

APTS representation in MITSIMLab is meant to include the representation of various APTS technologies and applications that generate, apply, or provide real-time transit performance information. Three broad categories of such APTS technologies and applications include:

- Surveillance and monitoring
- Real-time control of operations
- Traveler information dissemination

Surveillance and monitoring refers to APTS like AVL, APC and communications systems that generate or facilitate the sharing of real-time information. Real-time control of operations includes those APTS that use real-time information to control vehicle movements, either with or without TOC intervention. Finally, traveler information dissemination in MITSIMLab allows real-time performance data to be used to generate and provide information to travelers. In sections 5.4.1-5.4.3 below, the implementation of these three APTS functions in MITSIMLab is discussed.

5.4.1 Surveillance and Monitoring

Surveillance is a generic term used in this thesis to refer to the various detection and sensing technologies installed in the transportation network, on board vehicles or

centrally at a transit operations control center (TOC). The discussion of APTS representation in Chapter 3 and of various components of bus transit surveillance systems, such as GPS, communications systems and AVL in Chapter 2, indicate that both the technologies and the institutional implementations vary considerably. Therefore, it is an objective of the modeling effort in this research to develop the bus transit surveillance capabilities in MITSIMLab in such a way that it supports the simulation of any transit surveillance system. This means that MITSIMLab should be able to reproduce the kinds of information that various APTS technologies make available.

The discussion in Chapter 2 highlights three issues relating to real-time bus transit surveillance data that are taken into consideration in this research: ownership, storage and distribution. The issue of ownership has to do with which entity (e.g. bus, TOC, etc.) has possession of the data. Storage refers to the length of time an entity keeps the data before purging it, deleting it or sending it to another entity. Finally, data distribution deals with when and between which entities the information is shared. Through an accurate representation of data ownership, storage and distribution, MITSIMLab is able to represent any underlying AVL or other bus surveillance system.

Data Ownership

MITSIMLab mimics surveillance data ownership by tracking at all times a variety of transit performance variables with each component of the transit system. For example, buses are at all times "aware" of the following pieces of information:

- Bus type
- Location
- Current trip and route
- Design headway and prevailing headway
- Next scheduled arrival time and schedule deviation
- Passenger load

The information listed above provides a starting point for tracking a vehicle's progress throughout its work assignment. The information may be made available, according to the storage and distribution specifications described below, to other parts of the system

110

(e.g. TOC) for application to online APTS strategies. The bus' "knowledge" of it's type is key, because, by varying the bus type, the user may define a mixture of buses in the fleet that are or are not equipped with particular on-board technologies like APC systems and communications systems. For example, although all buses keep track of their passenger load at all times for dwell time calculations and performance measure output, the load information might not be used as input to APTS unless the bus is equipped with an APC system. Furthermore, a bus equipped with an APC system may collect and store load information, but may not share it with other parts of the system unless it is also equipped with on-board communications technologies.

All vehicles in MITSIMLab keep track of their current locations in the network. Buses also keep track of their current trips and routes. Since buses may serve more than one route through the course of an assignment, and will more than likely serve more than one trip on a single route, a bus always knows which route and trip it is serving in order to determine which bus stops it should serve. The combination of network-based and route-based location information can be accessed according to the storage and distribution characteristics of the surveillance system to mimic AVL and other vehicle location systems.

Buses in MITSIMLab also keep data about where they "should" be in terms of their schedules or design headways so that there is knowledge of whether the vehicle is ahead of or behind schedule. For vehicles with scheduled arrival times at stops, the bus "knows" its next scheduled arrival time, which it retrieves from the schedule to which it is assigned each time it arrives at a stop, in order to determine whether it is early or late when it arrives. Each bus keeps data about its deviation from the schedule at the previous bus stop, which may be used as input to such APTS applications as conditional bus signal priority that only grant priority if the vehicle is behind schedule. Dispatchers at the TOC might also use this information to devise holding, dispatching and expressing strategies for restoring service. Similarly, for buses that are assigned to frequent services with design headways rather than scheduled arrival times, a bus always knows its design headway as well as the time headway between itself and the bus that preceded it at the previous stop. Thus, conditional priority schemes and other real-time control strategies may make use of real-time headway information in MITSIMLab.

Data Storage

Storage properties of APTS surveillance technologies are of very little concern to MITSIMLab. Since MITSIMLab's purpose is to represent only those aspects of the technologies that affect vehicle and network performance, when and why data storage devices in the transit network purge certain pieces of information is not important. Storage becomes an issue with systems like AVL, where the vehicle's location information might be gathered from a GPS receiver on board and purged after it is sent to the TOC. When the TOC polls the vehicle to retrieve information, dispatchers are naturally only interested in the vehicle's most recent data. Since a TOC is able to store location information from previous transmissions, and since previous location information is no longer relevant, the TOC will probably not request, nor have the need for, data that may have already been purged on the vehicle. Thus, whether or not the data is kept or deleted on board the vehicle will not have an effect on how the surveillance system performs. MITSIMLab, for memory reasons, will generally only store the latest piece of information on each bus.

Data Distribution

Surveillance data distribution, which decides when information is delivered from one component of the transit system to another, is a function of the surveillance technologies and how they are put to use. Generally, the communications system determines how information is distributed among entities in the network. The way that information is shared is mostly governed by two elements: time and space. In terms of space, information might be shared locally, as between a moving vehicle and a roadside device, or regionally, as by a wireless network between vehicles and the TOC. In terms of time, information might be sent periodically at prespecified intervals or when prompted by the requesting device.

Locally distributed information, such as the passenger load and schedule deviation information that an approaching bus might deliver by radio signal to a signal controller to request priority, is modeled in MITSIMLab using sensors embedded in the network. The sensor, in effect, mimics the communication between the vehicle and the roadside device. A sensor can be placed in the network at a distance upstream of the

field-installed device (e.g. signal controller) that corresponds to the range of the transmitting and receiving devices. A sensor can be configured to respond only to certain vehicles (e.g. communications-equipped buses). When the sensor becomes activated in MITSIM, the relevant information is sent to the Traffic Management Simulator (TMS) in order to determine the response of the receiving device (e.g. signal controller).

Long distance communication, such as that between vehicles and the TOC, can be simulated by the communication between MITSIM and TMS. MITSIM periodically reports traffic data collected by its sensors to TMS, which uses the data in its traffic management logic. If buses transmit data periodically, as is the case with polling, a time step can be input to determine the frequency with which certain types of information are reported by MITSIM to TMS. Through a combination of sensors in MITSIM and MITSIM-TMS communication, distribution strategies like exception reporting, where a bus sends information only when a particular condition is met (e.g. it has reached a specified location in the network or when it is sufficiently behind schedule) can also be represented. Since each bus carries with it information about its progress, MITSIM can be instructed to send relevant bus data to TMS when the bus' schedule deviation or other performance variable breaches some predefined threshold. Similarly, to mimic exception reporting when a bus reaches a certain position in the network, sensors may be used. When this sensor becomes activated, MITSIM will send the relevant data to TMS. In this way, MITSIM sends data to TMS in the same way that transit vehicles in the real world, with the aid of APTS technologies, transmit data to field devices and to a TOC.

Vehicle location and other performance data is not only tracked to simulate real-time input to APTS strategies, but for writing data to output files that may be used to calculate measures of effectiveness for evaluating the performance of the APTS strategy. In section 5.5 is a description of the types of output that MITSIMLab generates for calculating transit system measures of performance.

5.4.2 Real-Time Control of Operations

The surveillance and monitoring implementation described above provides the basic infrastructure for simulating real-time control of operations. TMS' generic framework allows for the simulation of a boundless variety of traffic management

strategies. This capability is expanded in this research to support real-time transit fleet management strategies.

Control of operations might be manifested through traffic control devices (e.g. transit signal priority), or via communication with field supervisors or dispatchers at the TOC. For example, control device-based strategies like signal priority can be simulated by adapting TMS' current signal control logic to exploit incoming real-time transit data. Transit vehicles, then, merely react to the signal indication. TOC-based strategies, on the other hand, can be simulated by direct control of vehicle movements. For instance, speed control measures used by dispatchers to slow down or speed up transit vehicles may be implemented by directly manipulating the transit vehicle's desired speed. Likewise, stop-based control strategies like holding can be simulated by adding, and dynamically manipulating during a simulation, the conditions that must be met before a bus may depart from a stop. Since it is an enormous task to incorporate the functionality for all APTS control strategies into a simulator and since implementations vary from application to application, this research uses conditional signal priority to demonstrate the implementation of real-time control of operations in MITSIMLab.

In order to demonstrate the representation of APTS for real-time control of operations in MITSIMLab, conditional transit signal priority functionality is incorporated into the simulator. Davol (2001) developed a generic signal controller (refer to section 4.2.3) capable of simulating unconditional priority. For this thesis, conditional signal priority is incorporated into MITSIMLab in order to demonstrate the ability to simulate APTS that rely on a more detailed representation of transit operations. Some background information regarding transit signal priority is presented below, followed by a description of the implementation of conditional signal priority in MITSIMLab.

Background

Transit signal priority strategies may be categorized in a number of ways. Furth and Muller (2000) summarize signal priority strategies according to three dimensions:

- Active or passive
- Full, partial, or relative
- Unconditional or conditional

Active priority is triggered in response to the detection of an approaching bus, while passive priority involves no real-time responsive component, but rather involves a pre-timed signal timing plan that allots generous green times and progression bandwidths to favor a bus' approach. Full priority employs all priority actions (e.g. green extension, phase insertion, etc.), while partial priority uses a less disruptive, subset of priority actions for giving priority, and relative priority considers measured queues and traffic volumes on non-priority approaches before granting priority. Finally, unconditional priority assumes that all transit vehicles are granted priority, while conditional priority only grants priority to an approaching transit vehicle if the vehicle meets some predefined condition, such as whether the vehicle is behind schedule.

Transit signal priority was first introduced as a means of reducing transit vehicle travel times, and, thus, the first signal priority strategies were unconditional strategies (Furth and Muller, 2000). However, as increased delay to non-priority movements at an intersection became a cause of concern, the concept of conditional signal priority developed as a compromise between unconditional priority and no priority at all. Furth and Muller conducted a signal priority case study in Eindhoven, the Netherlands, and found that when priority is granted on the condition that the vehicle is behind schedule, substantial improvements could be achieved in schedule adherence without causing significant delays to conflicting approaches. Furth and Muller's (2000) Eindhoven results show that delay (time spent at speeds below 5 km/hr, other than at stops) increases by 100% on two non-priority approaches and by nearly 300% on another under unconditional priority. Schedule-based conditional priority, however, yielded significant delay reductions for transit vehicles, while causing only minor increases in delay to non-priority approaches.

Besides schedule adherence, the passenger load on a bus is another condition that has become a point of interest. The rationale for a minimum load requirement for priority provision is that priority should be given at an intersection only when net benefits can be achieved in terms of person throughput, or person delay, as opposed to vehicle throughput.

Implementation

The implementation of conditional transit signal priority in MITSIMLab relies on the MITSIM/TMS framework described in Chapter 4. Sensors in the network are used to mimic the communication between buses and traffic signal controllers. The input parameters that define traffic signal operations allow the user to include as an additional parameter the ID of a sensor with which it communicates. When a vehicle passes over such a sensor, the priority conditions are considered and, if they are satisfied, the sensor becomes "activated". When the sensor is "activated", the signal controller in TMS is informed that an approaching bus is requesting priority. The signal controller reevaluates the signal's status at every time step during a simulation and, when a bus is requesting priority, determines the appropriate priority action (e.g. green extension) given the signal's current state (Davol, 2001).

The condition thresholds for granting signal priority can be specified in an input file. The user may define one of 5 conditions:

- Load Only
- Headway Only
- Schedule Deviation Only
- Load & Headway
- Load & Schedule Deviation

These conditions can vary by time of day and by route. A sample conditional priority input file is given in Appendix E. The "load only" condition requires only that a bus requesting priority have at least a minimum passenger load in order to be granted priority. When headway is the only condition, priority is only granted if the time headway between the bus requesting priority and the previous bus on the same route is at or above some time headway threshold. Similarly, the schedule deviation threshold specifies how far *behind* schedule a bus must be in order to be eligible for priority. The combination conditions, such as load and headway, require that both conditions be satisfied.

The condition(s) are checked each time a bus arrives at a priority sensor. This mechanism for requesting priority is used to represent systems of communication that are employed in practice, such as a radio signal that transmits information stored on the

transit vehicle to a field-installed device, such as a signpost or a computer inside a signal control box. In the implementation it is assumed that the signal controller stores no information about passing buses, but only processes requests for priority. Thus, no request is sent if the bus does not meet the specified conditions. Therefore, information stored on the bus, such as the schedule deviation at the last stop and passenger load, are used to determine whether a request for priority is issued. Thus, the conditional priority implementation is capable of representing various types of APTS technologies, such as AVL, communications systems, and advanced passenger counting systems by representing the generation and conveyance of real-time performance information.

5.4.3 Traveler Information Dissemination

The representation of traveler information dissemination in MITSIMLab involves the conveyance of real-time travel information to transit passengers. The use of transit operations software (TOS) and advanced traveler information systems (ATIS) to generate information that travelers may use in their trip-making decisions can be implemented in TMS. The transit surveillance and monitoring functionality enables MITSIM to send real-time transit performance information (e.g. vehicle location, passenger load) to TMS, which executes the logic of the TOS or ATIS to generate traveler information. In effect, when TMS sends the traveler information to MITSIM, that information can be made available to "informed" users, where informed users may be travelers that have access to the Internet or wireless data transfer (e.g. cell phone or internet-capable personal digital assistant), travelers at particular stops (e.g. wayside/in-terminal information) or travelers on a particular vehicle or route (e.g. in-vehicle information). Then, through the use of traveler route choice models, traveler behavior may be simulated. The availability of real-time transit information to TMS provides a starting point for simulating ATIS and transit traveler behavior. However traveler behavior is outside the scope of this thesis and is left as a matter for future research.

5.5 Measures of Effectiveness

MITSIMLab generates a wealth of raw output data during each simulation. The output that a MITSIMLab simulation produces includes vehicle trajectories, vehicle trip summaries (e.g. origin, destination, departure time, arrival time, etc.), sensor readings, segment and link travel times, and segment statistics (e.g. traffic counts, densities, average speeds, etc.). Thus, MITSIMLab is capable of producing very detailed information about individual vehicles, segments, links and points (e.g. sensor dat) in the network. In order to evaluate transit performance, it is useful to generate the same kind of information about various components of the transit network (e.g. transit vehicles and bus stops). For example, the vehicle trajectory file is a record of each vehicle's speed and location in the network recorded every second during the simulation. A similar output file was created for transit vehicles, which records data such as passenger load, schedule deviation and other performance variables. Thus, the user may use transit trajectories to observe the passenger load profile along a route, and to observe the extent to which the vehicle strayed from or adhered to the schedule throughout the run.

Bus transit introduces a number of new dimensions in terms of measures of effectiveness. For example, passengers and passenger level of service must now be taken into account. The discussion in Chapter 3 identifies four levels at which transit performance measures are of interest:

- System
- Route Segment
- Stop
- Vehicle
- Passenger

System-level measures of performance, like aggregate travel time comparisons between transit vehicles and other modes, can be determined from vehicle trip summaries by separating the records by vehicle type. Route segment-level measures of performance, like mean speeds and mean travel times, can be extracted from MITSIMLab's vehicle trajectory and trip summary files, which can be decomposed according to vehicle type to attain values for buses. However, buses travel different routes, so the transit trajectory

file, which records route IDs, is useful for determining route-based performance measures. Since the transit trajectory file also records the bus' passenger load, the system-level passenger throughput can be determined.

Bus stop-level data is also used to determine route-level measures of performance such as mean headway. Each time a bus arrives at a bus stop, various pieces of information are reported to an output file. This information includes:

- Bus ID
- Route ID
- The bus' schedule deviation
- The headway between this bus and the last on the same route
- Dwell time
- Number of passengers arriving to board
- Number of passengers alighting
- Number of passenger left behind by a full bus

From the stop-level data, one can deduce the level of service at the stop from prevailing time headways and schedule deviations. The stop-level data also provides valuable information about how passengers arrive and alight at the stop and how this activity affects dwell times. Furthermore, one might compare dwell time variability at bus stops along a route to schedule adherence.

The transit trajectory file also stores data that is important for deriving vehicle-level performance measures, such as travel time, average speed, and schedule adherence. At constant intervals, a record is written for every bus in the network, including the following pieces of information:

- Time
- Route ID
- Bus ID
- Distance traveled from the origin
- Load
- Schedule deviation at the last stop
- Time headway with respect the preceding vehicle at the last stop

From this information, one may draw a number of meaningful conclusions about transit vehicle performance. This information, for example, is useful for determining the extent to which bus bunching occurs in the network and for determining the extent to which various vehicles in the network adhere to the schedule.

The bus stop and transit trajectory output files are also useful for calculating passenger level of service variables, such as aggregate travel times and waiting times. Recalling from the discussion passenger demand representation in Section 5.3, there is no representation of individual passengers in MITSIMLab, so no disaggregate passenger measures of performance can be determined. Furthermore, one must be aware of the type of service when making deductions about average passenger waiting time at a stop. For frequent services (e.g. headways less than about 12-15 minutes) one might presume that passengers arrive randomly and that the average waiting time is thus a simple function of the mean and standard deviation of the headway. However, for more infrequent services, one might require more information about passenger arrivals, such as the proportions of coincidental, optimal and random arrivals that Jolliffe and Hutchinson (1975) suggest, before drawing conclusions about passenger waiting time. However, one can make meaningful deductions about passenger performance measures when considering in-vehicle travel times and passengers that are left behind by full buses, as long as these conditions reflect reality.

Other outputs were implemented in MITSIMLab for use in the case study described next in Chapter 6. The case study is used to evaluate conditional signal priority. Thus, in order to determine how often priority conditions were satisfied and how varying the priority conditions affected the frequency with which priority was granted, a priority output file was created to record, each time a bus arrives at a sensor and requests priority, information about the bus (e.g. route ID, load, schedule deviation, headway) and whether priority is granted. This information is useful when attempting to prescribe condition thresholds that result in reasonable gains in transit performance without causing undue delay to the rest of the network.

Chapter 6

Case Study: Conditional Signal Priority

Chapters 1-5 discuss the development of a set of modeling requirements for simulating APTS and the incorporation of those requirements into MITSIMLab. In this chapter, the bus operations modeling and input features described in this thesis are tested on a portion of a bus rapid transit route in Stockholm, Sweden. The case study is used to evaluate conditional bus signal priority strategies along the route. This chapter describes the details of the case study, the evaluation methodology for determining the effectiveness of conditional signal priority in the network, and the results of the simulations.

6.1   Case Description

The purpose of this case study is to demonstrate the bus operations modeling capabilities in MITSIMLab by using the simulator to test and evaluate the performance of various conditional signal priority strategies in an urban network in Stockholm. A bus signal priority strategy called PRIBUSS was developed in Sweden for use throughout the Greater Stockholm area. PRIBUSS is of particular importance to three bus rapid transit routes that provide frequent service through inner Stockholm. The bus rapid transit routes are served by low-floor articulated buses, which use four sets of doors to serve boarding and alighting passengers. These articulated buses are equipped with GPS-based AVL systems that generate input to in-terminal/wayside traveler information systems and

various fleet management strategies such as signal priority. Furthermore, these buses are painted blue in order to distinguish them from other, more common buses, which are painted red. Less frequent bus routes in Stockholm are served by these red buses, which are neither articulated nor equipped with on-board GPS and AVL technologies.

The generic controller described in Chapter 4 has been used to evaluate PRIBUSS' unconditional signal priority logic on a single blue bus corridor in Stockholm (Davol, 2001). The same network, which is made up of a portion of a blue bus route and the surrounding area, is used in this case study to evaluate conditional signal priority. With the inclusion of the enhanced bus operations modeling features, this case study aims to achieve three things:

1. Demonstrate the simulation of APTS that rely on schedule information and real-time vehicle performance data.
2. Gather more meaningful information about the impacts of signal priority on transit performance and reliability.
3. Determine the extent to which conditional signal priority may achieve a compromise between delays to other traffic in the network and benefits to transit performance.

This case study examines several conditional signal priority strategies, which base priority provision on a combination of passenger load and headway conditions, and considers transit performance measures and network impacts as part of the evaluation process. The strategies are simulated under a number of scenarios in order to test each strategy's sensitivity to varying traffic conditions, such as increasing demand. Finally, recommendations are made for effective conditional signal priority implementation.

6.1.1 PRIBUSS: A Transit Signal Priority Strategy

PRIBUSS is designed to provide priority to buses without having excessive adverse effects on signal timings, particularly signal coordination, and thus on other vehicles in the network. PRIBUSS is able to alter a traffic signal's regular operation in one of four ways in order to provide priority to a vehicle that has been detected on the approach. These priority actions include:

- Green extension – Extend the current green period to allow time for the approaching bus to arrive at a green indication.

- Phase shortening – End the current phase early in order to change to an early green indication for the bus' approach.

- Extra phase insertion – Insert an additional phase, out of the ordinary sequence, in order to give a green indication to the approaching bus

- Green restart – The green restart is similar to the green extension, but occurs when the bus' green period has just ended. A new green period is initiated to allow the approaching bus to traverse the intersection.

The signal controller becomes aware of an approaching bus, and thus activates the PRIBUSS logic, when the bus passes a detector installed upstream of the intersection. In Stockholm, only the blue bus rapid transit vehicles, from here on termed "blue buses", are equipped with radio transmitters that send a signal to the detector. A second detector is installed just downstream of the intersection in order to indicate that the bus has passed and that the priority action may be halted.

When a bus is detected on an approach, the PRIBUSS algorithm determines the appropriate priority action based on the current status of the signals. Figure 6-1 illustrates the time periods in a typical 3-phase signal cycle during which each of the four priority actions is applicable.

Figure 6-1: PRIBUSS priority actions during a typical 3-phase cycle (source: Davol, 2001)

Group 1 is the group of movements that includes the bus' movement, to which priority may be granted. Group 2 is the group of movements that are given green after Group 1, and Group 3 is the group of movements that have a green indication prior to Group 1. From the diagram it can bee seen that, if a bus is detected during its own green indication, then the green extension will be called, unless the bus has time to traverse the intersection within the regular green period. Green start takes precedence if the bus is detected after its green period has already ended and before the beginning of the Group 2 phase that normally follows. Note that a green indication in Stockholm is preceded by a simultaneous yellow and red indication to mark the beginning of a green period. Extra phase insertion is applicable when the bus is detected during the Group 2 phase but before the start of the Group 3 phase, and phase shortening may be applied when the bus is detected during the startup yellow/red or green indications in Group 3's phase.

6.1.2 Study Network

Inner Stockholm is made up of a cluster of islands, the southernmost of which is Södermalm. The study network includes three major arterials that converge at the western end of Södermalm in a commercial hub called Hornstull. One of Stockholm's bus rapid transit routes traverses the study network, which is shown in Figure 6-2. The intersection at Hornstull joins Liljeholmsbron, a bridge that enters Södermalm from the southwest, Långholmsgatan, which is a major arterial between Hornstull and northern Stockholm, and Hornsgatan, which runs northeast through Södermalm into the southern portion of central Stockholm. Liljeholmsbron is a key entry point into Stockholm from the southwest and carries heavy morning traffic into the city by way of the Hornstull intersection, where the flow is split between Långholmsgatan and Hornsgatan. The cross-street traffic in the study network is relatively low compared to the traffic on each of the three main arterials due, in part, to street closures that prevent drivers from overloading alternate, minor streets to avoid congestion on the arterials.

There are six signalized intersections and one signalized pedestrian and bicycle crossing in the network. Figure 6-3 shows the locations of the signals in the network. During the day, the signals along the network are pre-timed and coordinated. The coordination is designed to provide bi-directional progression along the corridor formed

by Långholmsgatan and Hornsgatan at 43 km/h (27 mph). The speed limit along the corridor is 50 km/h (31 mph).
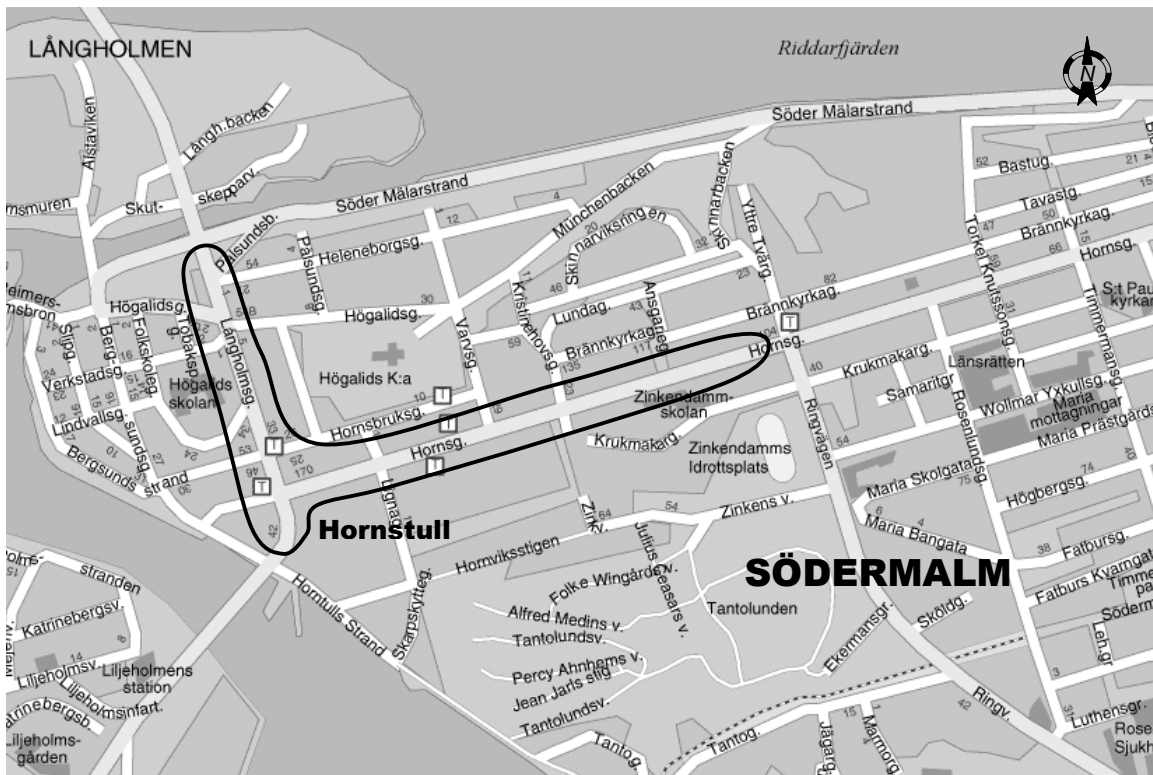
Figure 6-2: Study area on the western end of Södermalm

The PRIBUSS priority logic is installed in all signals in the network. However, the "restart green" action is not applied in this network since the minor cross street movements are allotted such short green times from the outset that it is not practical to reduce the phase following a priority green period in order to restart a priority green indication. Furthermore, the "phase insertion" action is only permitted at the intersection at Hornstull for the buses turning left onto Hornsgatan from Långholmsgatan. Bus detectors (radio signal receivers) are located upstream and downstream of every intersection. The detection points for approaching buses are typically located 150 to 180 meters upstream of an intersection, allowing 12.5 to 15 seconds to reach the intersection at the signal progression speed. Where bus stops are located just upstream of an intersection, the bus does not send a signal until the doors are closed and the bus is ready to proceed.
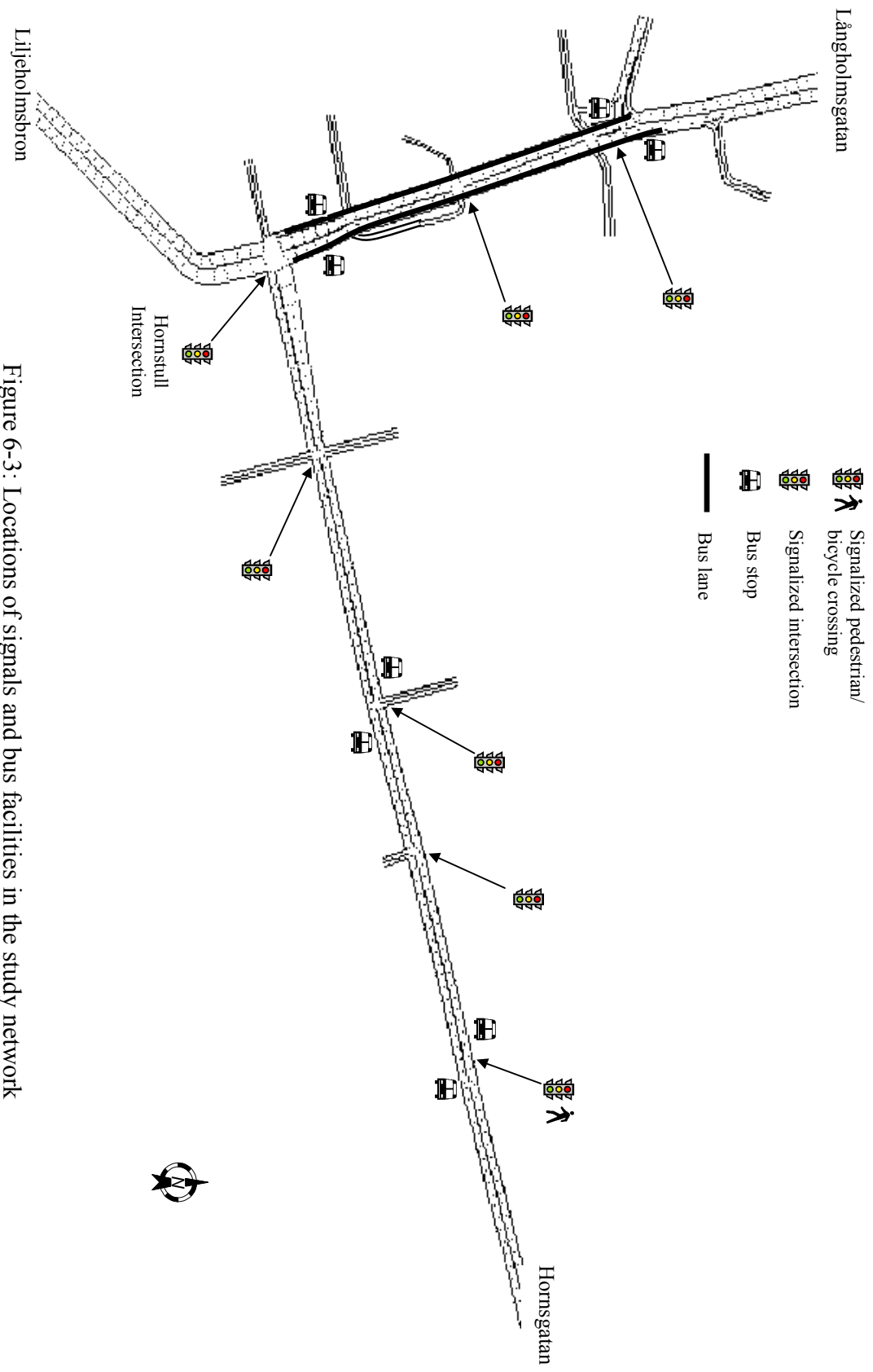
Figure 6-3: Locations of signals and bus facilities in the study network

126

Three local red bus routes and one blue bus route operate within the study network. Buses that serve the red bus routes have 15-minute headways during the peak periods, and the articulated buses that serve the bus rapid transit route operate at 7.5-minute headways all day. The locations of bus stops and bus lanes in the study network are also shown in Figure 6-3. Again, only blue buses are equipped to communicate with the sensors in the network in order to request priority. Figure 6-4 indicates where the bus routes operate in the network.
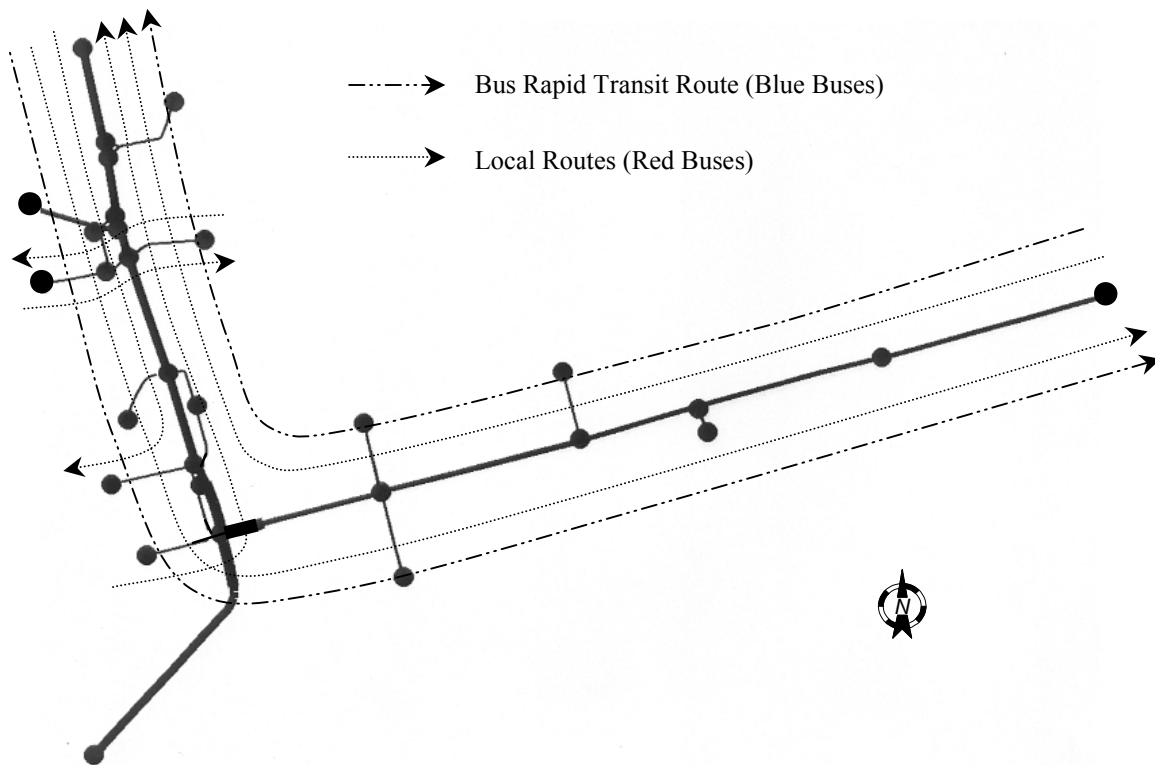
Figure 6-4: Bus routes in the study network

Three red bus routes travel through the study network, one that crosses Långholmsgatan at the top of the network, one that runs north and south along Långholmsgatan, and one that shares the blue bus path along Hornsgatan and Långholmsgatan. The one blue bus route in the network runs in both directions along Hornsgatan and Långholmsgatan. The focus of the case study is on the bus rapid transit route, to which priority is provided. Thus, transit performance measures in this chapter will emphasize blue bus operations. However, buses that serve the local red bus routes share all bus stops along their paths

with the blue buses, thus it was important to simulate red bus operations in order to account for the impacts of red bus operations on that of blue buses. The bus stops in the study network, as well as in MITSIMLab, allow for simultaneous passenger loading by buses on different routes.

6.1.3 Previous Application

A previous case study with the same Stockholm network was conducted to test the functionality of the generic signal controller in MITSIMLab's Traffic Management Simulator (TMS) (Davol, 2001). The case study was used to evaluate the performance of the PRIBUSS priority strategy for granting unconditional priority to buses serving the bus rapid transit route along Hornsgatan and Långholmsgatan. At the time of the case study, MITSIMLab relied on a simplistic representation of buses, bus routes, bus stops and bus lanes.

The previous study examined effects of each of the priority actions separately and in combination at those signals where such actions are allowed. The primary measure of performance for evaluating the benefits and adverse effects of priority was travel time. Priority is expected to have different impacts on various types of vehicles. For this reason, vehicles are separated into buses (blue buses only), northbound buses (blue buses traveling from Hornsgatan to Långholmsgatan), southbound buses (blue buses traveling from Långholmsgatan to Hornsgatan) and "other" vehicles, which includes non-transit vehicles with side origins and non-transit vehicles with arterial origins.

Priority is expected to reduce transit vehicle travel times. Davol (2001) found that blue bus travel times are reduced by 17.6% on average when all permissible priority actions are employed. The greater average travel time reduction for southbound buses with respect to northbound buses is a result of the signal timings at the Hornstull intersection, where left-turning buses are treated as a separate signal group, and are given 6 seconds of the total 100-second cycle length. Northbound buses turning right onto Långholmsgatan, on the other hand, enjoy 49.5 seconds of the 100-second cycle. Furthermore, Davol (2001) learned from observing simulation runs that the coordinated signal timings also favor the northbound buses, especially when a northbound bus departs from a bus stop to join a platoon destined for a green period downstream. Thus, priority

has a much greater potential for travel time reduction for southbound buses than for northbound buses.

Some non-transit vehicles, particularly those that enter the network on one of the arterials (i.e. "arterial origins") rather than a minor side street, are also expected to benefit from priority, since the vast majority will share the through movements along Hornsgatan and Långholmsgatan with buses on the same approach. Other vehicles, however, namely those entering from a side street origin (i.e. "side origins"), are expected to suffer added delay as a result of priority, since the green time that is normally allotted to their movements will be shortened and/or delayed in order to provide additional green time to conflicting priority movements. Davol (2001) also found that non-transit vehicles with arterial origins enjoy a modest average travel time decrease of 2.4%, while non-transit vehicles with side origins suffer an average increase in average travel time of 1.8%.

The conclusions drawn from the previous case study lead to the recommendation that all permitted PRIBUSS priority actions be applied in the network in order to achieve the greatest transit travel time savings with minimal delay caused to other vehicles. The case study conducted for this thesis expands the scope of the previous work to create an opportunity to further the lessons that may be learned from APTS simulation.

6.1.4 Conditional Signal Priority

The case study used to demonstrate the bus operations and APTS simulation capability described in this thesis is conducted to evaluate conditional bus signal priority in Stockholm. In the case study, the recommendations from the earlier work described above are followed, and thus all allowed priority actions are applied at all signals. The difference between the strategies considered in this case study and the last is between conditional and unconditional priority. All approaching blue buses were granted priority in the previous case study. This case study proposes to introduce conditions to the provision of priority to blue buses.

This case study seeks to evaluate and compare the transit and general traffic performance measures that result from five priority implementations:

- No priority (Base Case)
- Unconditional priority

129

- Conditional priority with only a minimum load threshold
- Conditional priority with only a maximum headway threshold
- Conditional priority with load and headway thresholds

The schedule condition will be treated in terms of time headway, since the blue buses operate according to a design headway rather than scheduled arrival times. A minimum load threshold is a minimum load that a bus must carry in order to be eligible for priority.

A maximum headway threshold is a headway above which a bus is eligible for priority. Thus, when a headway is very short with respect to the design headway, a bus is considered ahead of schedule and will not be granted priority. A headway greater than the maximum threshold indicates a bus that is behind schedule, which thus should be granted priority in an attempt to restore the design headway and reduce the waiting times of the passengers downstream. The term *maximum* threshold is used because a headway above this threshold is undesirable. However, like the load condition, the headway condition acts like a minimum threshold at which a bus must be operating in order to be granted priority. For this case study, it is assumed that the signal controller does not store information about passing buses, and thus gets all of its information via communication with the approaching bus. The bus records its prevailing headway at each bus stop as the time elapsed between its arrival and the arrival of the previous bus on the same route at the same stop. This headway is stored on the bus and transmitted to the signal controller when it is detected on the approach to an intersection. The combination of load and headway thresholds requires that *both* conditions be met in order to be granted priority.

Five measures of performance are considered in this case study to determine the extent to which each of the priority implementations affects the transit and overall transportation system performance. These measures of performance include:

- Travel time per vehicle
- Travel time variability
- Total Person travel time
- Headway variability

The first measure, travel time, is the time a vehicle spends in the study network, and thus is a strong indicator of the delay that vehicles suffer due to congestion and queues at

signalized intersections. Thus, travel time may be used to compare the reduction in transit vehicle running time to the travel times of other vehicles in the network. Travel time variability is used as an indicator of transit level of service, where high travel time variability is tends to accompany poor service reliability. Headways along a transit route are another good indicator of transit service quality, since longer headways (with respect to the desired headway) indicate longer passenger waiting times. Headway variability, in particular, has direct relevance to the passenger experience. As service becomes more irregular (i.e. high headway variability), long headways become more common and more passengers are made to suffer longer waiting times. Finally, person travel time is considered in order to examine how different strategies affect the amount of time individual persons, rather than vehicles, spend in the network.

6.2 Simulation Preparation

Preparing a network for simulation in MITSIMLab requires a lot of detailed input data. This data includes driving and behavior model parameters, network geometry, origin-destination demand data, signal control logic and parameters, fleet mix and vehicle type parameters, and, for transit applications, transit network, schedule and assignment data and passenger demand data.

The driver and travel behavior parameters applied in this case study were calibrated and validated against data collected on a separate Stockholm network in 2000 (Ben-Akiva et al., 2002). These calibrated parameters are expected to yield simulated conditions that reflect real-world driver and traveler behaviors in Stockholm.

The Hornstull roadway network representation was produced as a part of the previous case study conducted by Davol (2001). Gatu- och Fastighetskontoret (GFK), the administration in charge of traffic planning and operations in Stockholm, provided maps and aerial ortho-photographs of the network. These maps and photographs were used to construct a link-node representation of the network and to specify the locations of bus stops, bus lanes, traffic signals, surveillance devices and other facilities in the network. The transit routes and bus stop locations were determined from maps published by Storstockholms Lokaltrafik (SL), the Greater Stockholm public transit agency. Minor

modifications of the network geometry were made in order to accommodate the updated bus operations representation. Bus lanes were modeled in a more explicit manner, and bus stop lengths were specified in order to allow red and blue buses to serve stops simultaneously when they arrive coincidentally at a stop served by both routes.

An origin-destination matrix for private automobile and truck travel demand was developed from the following sources of information:

- 15-minute aggregate traffic counts on various days between 1998 and 2000
- Estimated 24-hour aggregate flows for all roads in the network from 1994
- Turning movement counts at the Hornstull intersection from 1988.

Of the 15-minute aggregate counts ranging between 1998 and 2000, the most recent counts were measured in September 2000 at the locations indicated in Figure 6-4.
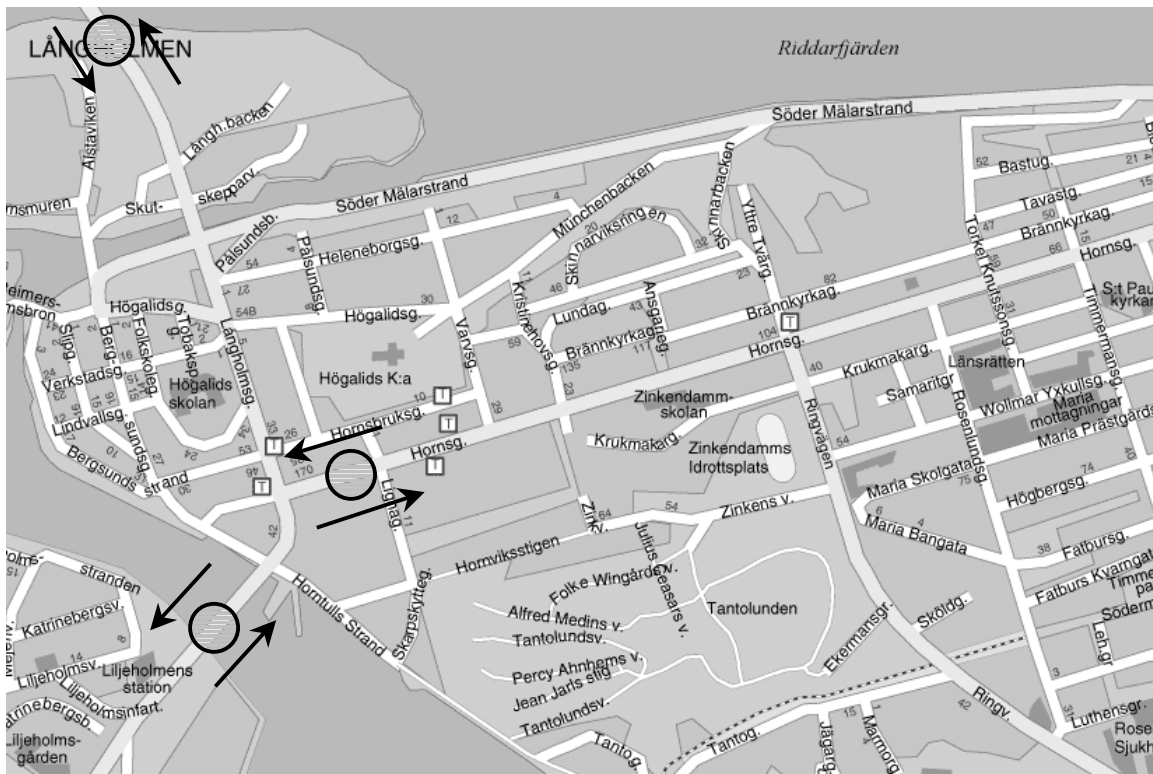
Figure 6-5: Locations of 15-minute aggregate counts in September 2000

These counts were collected during the morning peak hour between 7:30 and 8:30 AM. The morning peak traffic counts show little variation in time. Using this data, an O-D

132

matrix was estimated for the morning peak hour, the chosen period of interest for the case study. Blue bus operations were also specified in the O-D input file in order to simulate frequent service of the bus rapid transit route without scheduled arrival times.

GFK also provided traffic signal timing plans for all signals in the network. Davol used these timing plans to generate the traffic control parameter input files that govern how the signals operate in MITSIMLab. Davol created several control parameter input files for various PRIBUSS implementations (e.g. varying priority actions). These input files were used in the case study. However, the parameters that govern bus detection were modified to simulate conditional priority. According to the discussion of bus transit surveillance modeling in Chapter 5, sensors were used to mimic the communication between signal controllers and approaching blue buses. The conditional priority input file, an example of which is shown in Appendix D, allows the user to specify the conditions (e.g. minimum load, maximum headway) that apply to specified routes in the network. The signal timing at the signalized pedestrian/bicycle crossing on Hornsgatan was estimated from call frequencies provided by GFK.

The total vehicle fleet mix is divided into heavy vehicles (e.g. trucks), buses and automobiles. The heavy vehicle proportion of the vehicle mix was estimated by classified peak hour count data from 1999. The bus headways in the network were taken from schedule timetables published by SL.

Transit schedule data was required in order to model red and blue bus services. Blue buses are scheduled to serve the route at 7.5 minute headways, or 8 blue buses per hour. However, the time from the start of the simulation until the first blue bus enters the network is allowed to vary stochastically according to a Poisson distribution. After the first blue bus enters the network, the time headway between subsequent blue buses is constant. This is the equivalent of assuming that blue buses enter the network "on schedule". Thus, the randomness in travel times, signal delays and passenger demand that affect bus operations is limited to what takes place within the boundaries of the study network.

Since red bus operations are not a focal point of the case study, schedule definitions were specified with empty scheduled arrival time arrays. Scheduled arrival times in MITSIMLab do not affect bus operations unless control strategies that require

schedule information are simulated. Thus, it was not necessary to specify the scheduled arrival times at stops for the red buses. However, published schedules from SL indicate that red buses operate at 15-minute headways. Thus, bus assignment input files were created to generate red buses at the appropriate origins of the network at 15-minute intervals. Since only portions of the bus routes fall within the network boundaries, run definitions for red and blue buses in the network amount to a single trip from the "origin" node of the study network to the "destination" node.

Bus operational parameters were also required in order to simulate red and blue bus operations in the network. A number of assumptions were made regarding passenger demand and boarding and alighting parameters in the absence of available input data. Davol modeled bus dwell times as randomly drawn from a uniform distribution between 15 and 45 seconds, thus with an average dwell time of 30 seconds. To reproduce these same general conditions and to achieve realistic base case results in terms of dwell times, travel times and headways, the passenger demand rates at each stop in the network were assumed to be 60 passengers per hour and 90 passengers per hour for red and blue buses, respectively. Similarly, since the study network generally serves "through" trips, trips that originate from and are destined to points located outside of the network, alighting rates (percentage of the bus load alighting) at each stop in the network were assumed to be 10%. Thus, the passenger demand was assumed to be evenly distributed along the portions of the routes within the study network. Furthermore, since the private automobile and truck travel demand does not vary significantly during the morning peak hour, passenger demand for the transit routes was also assumed to be constant.

Operational and physical characteristics of red and blue buses were also specified with some assumptions. The input parameters are shown in Table 6-1. The parameters shown in italics were estimated with guidance from the Transit Capacity and Quality of Service Manual (Kittelson & Associates, 1999). The TCQM recommends boarding and alighting times for buses of various types. Red buses are standard one-door buses, for which the TCQM recommends average boarding and alighting rates of 2.6 and 1.7 seconds, respectively.

Table 6-1: Operational parameters relevant to bus operations

Parameter	Red Bus	Blue Bus
Length (feet)	40	60
Seating Capacity	32	46
Total Capacity	70	124
Average Boarding Rate (seconds/passenger)	2.6	2.2
Average Alighting Rate (seconds/passenger)	1.7	1.4
Dwell Time Lower Bound (seconds)	2.0	2.0
Dwell Time Upper Bound (seconds)	5.0	5.0
Crowding Factor (seconds)	0.5	0.5

The blue buses are articulated buses with low floors and four sets of doors. However, at present, Stockholm has not yet implemented a smart card electronic fare collection system, so passengers must all board at the front door. Some passengers pay with swipe-card passes (e.g. monthly passes), some pay with cash and must be given change by the operator, and others pay with a ticket that must be stamped by the operator. Thus, boarding and alighting rates of 2.6 and 1.7 seconds, respectively, for conventional, single-door buses with non-prepaid fare collection were assumed. However, the TCQM recommends multiplying the boarding and alighting rates by 0.85 if the bus has low floors. Thus final boarding and alighting rates of 2.2 and 1.4 seconds, respectively, were used for blue buses. The TCQM also recommends adding 0.5 seconds to the boarding rates when standees are present on the bus. Lastly, dead times were allowed to vary between 2.0 and 5.0 seconds, according to typical values measured by Levinson (1983).

6.3 Evaluation Approach

The evaluation approach adopted in the case study is to examine the effects of various transit signal priority strategies on transit and network performance, with special emphasis on conditional priority. A sensitivity analysis is conducted to determine how varying thresholds within the priority conditions affect transit and network performance measures. The study considers three schools of thought regarding the purpose of signal

priority and the implications these philosophies have with respect to the levels of service enjoyed by various types of users in the network. These schools of thought include:

- Improved person throughput
- Reduced transit travel times
- Improved transit reliability (and thus passenger level of service)

The purpose of the case study is to estimate the extent to which different signal priority implementations achieve the objectives listed above, while taking into account other impacts, such as the average travel times of all vehicles in the network.

It is important to explore the effects that a technological solution brings to bear on different types of users in the network. The measures of effectiveness used in this research to compare the costs and benefits of transit signal priority include travel time, travel time variability, and total person travel time, categorized by the following vehicle types:

- all vehicles,
- blue buses,
- southbound blue buses,
- northbound blue buses,
- non-transit vehicles,
- non-transit vehicles entering on a side street (non-priority),
- and non-transit vehicles entering the network on one of the arterials.

By examining the impacts on travel time, one may determine the reduced and added delay to different types of vehicles in the network. On the other hand, to determine the reduced and added delay to individuals in the network, total person travel time is considered. Travel time variability may be used as an indicator of transit reliability. However, to gain more insight into the impacts of signal priority on schedule adherence, headway and headway variability is examined for bus rapid transit (blue bus) operations along Hornsgatan and Långholmsgatan.

Travel times and travel time variability are computed using MITSIMLab's vehicle trip summary output, which records information about every completed trip (departed at entry node to network and arrived at an exit node) in the network, including vehicle ID,

vehicle type, origin, destination, departure time, arrival time, distance traveled and average speed. From this information, performance measures may be extracted and classified by vehicle type, path, or other category of interest.

Total person travel time is computed as the sum total time spent in the network for all individuals over all simulations for a given scenario. Travel time for individuals traveling by auto or truck is the travel time, taken from the vehicle trip summary, multiplied by an assumed average vehicle occupancy of 1.2 to get total person-hours spent in the network. For transit passengers, the time spent in the network is computed from the transit trajectory file, which records at every second during the simulation each bus' vehicle ID, route ID, trip ID, position, speed, passenger load, schedule deviation at the last stop and headway at the last stop. Thus, for each second in the simulation, the passenger load on each bus is known, so passenger-seconds spent in the network is calculated by summing the passenger loads from all records in the transit trajectory file. The transit trajectory file is also used to observe bus trajectories (time-space diagrams) through the network for different priority implementations.

Mean headways and variability are determined from the bus stop output file, which creates a record every time a bus arrives at a bus stop, recording the bus stop ID, bus ID, route ID, schedule deviation, headway on the given route, dwell time, number of passengers wishing to board, number of passengers alighting and number of passengers left behind. Thus, the bus stop output file is also used to observe the relationships dwell time and passenger arrivals.

The time period of interest in the case study is 7:30 to 8:30 AM, the morning peak hour. The number of simulation runs, or observations in a sample, required to obtain reliable estimates of output measures of performance is given by:

$$R = \left(\frac{t_{\alpha/2} s}{e} \right)^2$$

where

        R = number of required simulation runs, or observations
        $t_{\alpha/2}$ = critical value of the t-distribution at a level of significance α,

        s = estimated value of the standard deviation of y^s,

        e = allowable error (in the same units as y^s).

The measure of performance with the highest standard deviation will determine the number of required observations. Davol (2001) found that the limiting measure of performance was average bus travel time due to the relatively small number of buses per simulation run. Davol found that, for 10 runs, the estimated error in average bus travel time is ± 1.1% at a 95% confidence level. The estimated error in average non-transit travel time for 10 runs at a 95% confidence level is ± 0.25%. These errors are considered to be acceptable for the purposes of this case study.

The base case for the case study is the network under normal peak hour demand without priority. Other scenarios include unconditional priority and various conditional priority strategies with varying conditions (e.g. load, headway, etc.) and varying thresholds (e.g. minimum load of 30 passengers). The robustness of the strategies is also tested under scenarios of increased demand.

6.4   Results

Travel time and travel time variability, person travel time and headway variability results from simulations of the priority strategies are presented and discussed in the sections that follow. A priori, one expects to see certain changes in these performance measures depending on the priority implementation. Some general a priori expectations that were held before the simulations were begun are:

- Greater travel time savings to blue buses and greater increases in travel time costs to non-priority movements should arise as the conditions for priority become less stringent, with the greatest blue bus savings and greatest non-priority travel time costs occurring under unconditional priority.

- Greater person throughput (i.e. lower person travel time) should result from load-based conditional priority strategies, which are designed to strike a balance between delay to all travelers, both automobile and transit.

- Better schedule reliability (i.e. lower headway variability) should result from headway-based conditional priority strategies, which are meant to provide priority only to "late" transit vehicles in order to maintain a desired headway.

The results from a number of simulations are discussed below in the context of each of the performance measures of interest. A parameter sensitivity analysis designed to test the sensitivity of transit and network conditions to the conditional priority thresholds is conducted throughout the case study by varying the condition thresholds. Further simulations are performed to explore the effects of increased demand.

6.4.1 Vehicle Travel Time

Average travel times per vehicle for AM peak hour conditions are given in Table 6-2. The aggregate vehicle travel time results are categorized by vehicle type: all vehicles, blue buses (all, northbound, southbound), and non-transit vehicles (all, those entering on a minor street, those entering on an arterial). The red buses are considered only among "all vehicles" in order to single out blue buses as the beneficiaries of signal priority. Red buses, like non-transit vehicles with arterial origins, may also benefit from priority when they arrive at a signal that has granted priority to a blue bus, and these benefits are accounted for in the vehicle travel times as well as the person travel times in section 6.4.3.

The non-transit vehicles with side origins are those non-priority vehicles that will be directly affected (i.e. delayed) by priority to arterial signal groups. Non-transit vehicles with arterial origins are distinguished from those with side origins since they are likely to benefit to some degree from priority when they arrive at a signal that has granted priority to a blue bus. Arterial origins are defined as the network endpoints of Hornsgatan and Långholmsgatan. Although Liljeholmsbron is also an arterial street, it is considered a "side street" since it is a non-priority entrance to the network (i.e. no bus routes travel on the street). Non-transit vehicles that enter and leave the network with minimal or no interaction with the traffic signals are not included anywhere in the analysis. The priority rate shown in Table 6-2 is the percentage of all blue bus priority requests that satisfy the condition(s). Whether priority may actually be granted, however, depends on the PRIBUSS logic and when in the signal cycle the bus arrives.

Table 6-2: Aggregate travel time comparisons by vehicle type

Priority Strategy	Condition(s)		Priority Rate (%)	Average Travel Time (seconds)						
	Load (# pass.)	Headway (minutes)		All Vehicles	Blue Buses			Other Vehicles		
					All	South-bound	North-bound	All	Side Origins	Arterial Origins
No Priority	-	-	-	113.1	260.9	317.1	204.8	112.4	108.9	116.5
Unconditional	none	none	100%	113.3	212.6	237.3	188.1	112.8	110.6	115.3
Load Only	> 20	-	76%	113.7	218.2	244.2	192.3	113.2	109.9	117.0
	> 30	-	64%	113.4	223.8	256.6	191.5	113.0	109.8	116.7
	> 40	-	33%	113.4	243.3	290.9	195.7	112.9	109.6	116.7
Headway Only	-	> 7.5	47%	113.4	228.7	265.2	192.7	112.9	109.7	116.6
	-	> 8.0	23%	113.3	234.6	277.0	192.2	112.7	109.4	116.6
	-	> 8.5	9%	113.2	248.7	296.3	201.0	112.7	109.2	116.7
Load & Headway	> 15	> 7.5	42%	113.4	245.3	291.6	199.0	112.8	109.3	116.8
	> 30	> 7.5	33%	113.4	258.0	309.4	206.5	112.8	109.3	116.9

It can be seen from Table 6-2 that average blue bus travel times do significantly decrease as the priority conditions become less restrictive, with the lowest average travel times occurring under unconditional priority. A plot of average travel times by vehicle types and priority strategies in Figure 6-6 shows the travel time savings from the least restrictive load-only and headway-only conditional strategies compared to no priority and unconditional priority.
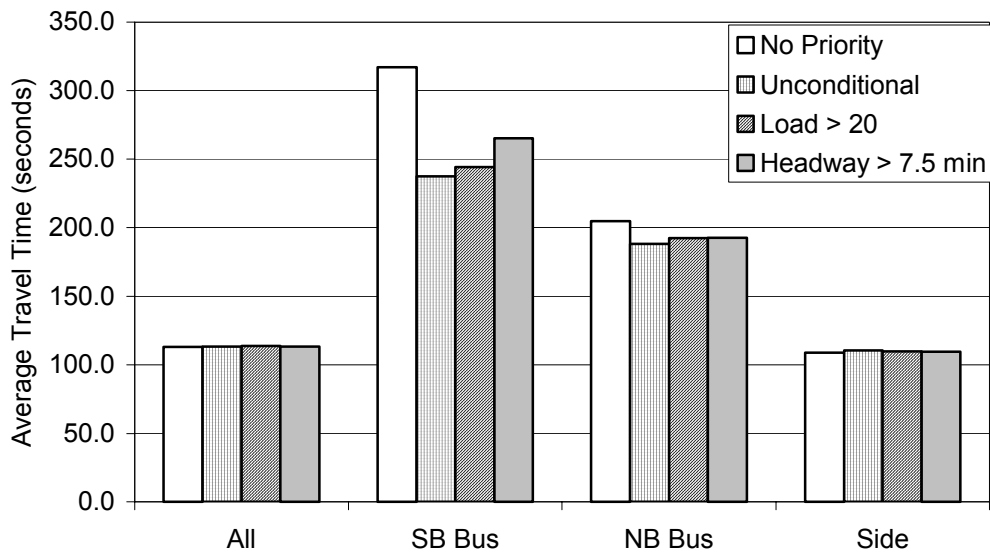
Figure 6-6: Average travel time for select vehicle types and priority strategies

The mean travel time for northbound buses is in all cases considerably lower than that of the southbound buses. This is due to the increased delay to southbound buses at the Hornstull intersection described earlier in section 6.1.3. However, since the demand

on the side streets in the study network is very low, the impact on non-transit, non-priority vehicles entering the network from the side origins is not substantial. On average, the increase in travel time to a vehicle with a side origin is only 1.7 seconds between the unconditional and no priority implementations.

The percent change in average travel time from the base case for each priority strategy is shown in Table 6-3. When considering all vehicles together, it can be seen that only a very small increase in average travel time results from any one of the priority implementations. The greatest travel time savings for any priority strategy accrue to the blue buses, particularly the southbound buses. While blue buses see appreciable benefits, the increase in travel time experienced by non-transit vehicles with side origins is marginal. Non-transit vehicles with arterial origins do not see substantial benefits with any priority strategy. Travel time reduction for non-transit vehicles of arterial origins occurs only in the unconditional priority case.

Table 6-3: Percent change in average travel times from the base case

Priority Strategy	Condition(s)		Priority Rate (%)	% Change in Travel Time from Base Case						
				All Vehicles	Blue Buses			Other Vehicles		
	Load (# pass.)	Headway (minutes)			All	South-bound	North-bound	All	Side Origins	Arterial Origins
No Priority	-	-	-	-	-	-	-	-	-	-
Unconditional	none	none	100%	0.18%	-18.51%	-25.17%	-8.15%	0.36%	1.56%	-1.03%
Load Only	> 20	-	76%	0.53%	-16.37%	-22.99%	-6.10%	0.71%	0.92%	0.43%
	> 30	-	64%	0.27%	-14.22%	-19.08%	-6.49%	0.53%	0.83%	0.17%
	> 40	-	33%	0.27%	-6.75%	-8.26%	-4.44%	0.44%	0.64%	0.17%
Headway Only	-	> 7.5	47%	0.27%	-12.34%	-16.37%	-5.91%	0.44%	0.73%	0.09%
	-	> 8.0	23%	0.18%	-10.08%	-12.65%	-6.15%	0.27%	0.46%	0.09%
	-	> 8.5	9%	0.09%	-4.68%	-6.56%	-1.86%	0.27%	0.28%	0.17%
Load & Headway	> 15	> 7.5	42%	0.27%	-5.98%	-8.04%	-2.83%	0.36%	0.37%	0.26%
	> 30	> 7.5	33%	0.27%	-1.11%	-2.43%	0.83%	0.36%	0.37%	0.34%

The reduction in travel time for blue buses is as high as 25% for the southbound buses, which occurs in the unconditional priority case. Table 6-3 shows that conditional priority strategies, namely when the minimum passenger load is 20, can achieve approximately the same benefits (23% travel time reduction) as unconditional priority with a lesser penalty to side street traffic. However, the change in average travel time for side street vehicles for different priority strategies is too low to draw general conclusions about the tradeoff between transit travel time savings and side street travel time penalties.

The results in Table 6-3 suggest that combination load/headway conditions are probably too restrictive and thus do not yield significant benefits in terms of blue bus travel time savings. A load threshold of 15 and a headway threshold of 7.5 minutes can improve southbound travel times by up to 8%, but does little for northbound blue bus operations. When the combination condition becomes even more restrictive, with a load threshold of 30, little or no improvement in blue bus travel time occurs.

6.4.2 Travel Time Variability

Travel time variability is an important measure of performance from the standpoint of traveler level of service. The transit passenger benefits from lower travel time variability because transit service becomes more regular, predictable and reliable as travel time variability declines. Likewise, private auto drivers and their passengers benefit from reduced travel time variability because the total journey time they expect becomes more commensurate with the travel times that they experience. The standard deviation of travel time is used as a measure of the variability in travel time in the network. The standard deviations of travel time, categorized by vehicle type, are provided in Table 6-4. The percent changes in standard deviation of travel time from the base case (no priority) are given in Table 6-5.

Table 6-4: Standard deviation of travel time by vehicle type

Priority Strategy	Condition(s)		Priority Rate (%)	Standard Deviation of Travel Time (seconds)						
	Load (# pass.)	Headway (minutes)		All Vehicles	Blue Buses			Other Vehicles		
					All	South-bound	North-bound	All	Side Origins	Arterial Origins
No Priority	-	-	-	43.5	83.2	70.3	51.0	41.8	36.9	46.5
Unconditional	none	none	100%	42.6	48.0	43.3	39.1	41.6	37.4	45.9
Load Only	> 20	-	76%	43.3	54.2	52.4	42.4	42.2	37.1	47.1
	> 30	-	64%	43.4	57.3	52.9	40.9	42.2	37.2	47.1
	> 40	-	33%	43.5	71.3	64.2	38.9	42.2	37.4	46.8
Headway Only	-	> 7.5	47%	43.2	54.7	44.2	37.6	42.0	37.2	46.6
	-	> 8.0	23%	43.4	59.6	44.2	39.5	42.2	37.3	47.0
	-	> 8.5	9%	43.7	73.3	66.1	43.0	42.3	37.2	47.1
Load & Headway	> 15	> 7.5	42%	43.5	75.1	73.6	43.2	42.1	37.0	47.0
	> 30	> 7.5	33%	43.5	71.4	56.5	41.2	42.1	37.1	46.8

Similar to the average travel time comparisons, Table 6-4 shows that travel time variability can be reduced to the greatest extent when the conditions are least restrictive. While the impacts on the travel time variability for side street traffic are again too small

to detect any definite trends, it is interesting to note that, with a minimum headway threshold of 7.5 minutes (i.e. the design blue bus headway), conditional priority can achieve about the same reduction in blue bus travel time variability as unconditional priority while granting priority only 47% of the time. Load-only and combination load/headway conditions also appear to lower travel time variability in general, but to a lesser extent, which is consistent with a priori expectations.

Table 6-5: Percent change in standard deviation of travel time from base case

Priority Strategy	Condition(s)		Priority Rate (%)	% Change in Standard Deviation of Travel Time from Base Case						
				All Vehicles	Blue Buses			Other Vehicles		
	Load (# pass.)	Headway (minutes)			All	South-bound	North-bound	All	Side Origins	Arterial Origins
No Priority	-	-	-	-	-	-	-	-	-	-
Unconditional	none	none	100%	-2.07%	-42.31%	-38.41%	-23.33%	-0.48%	1.36%	-1.29%
Load Only	> 20	-	76%	-0.46%	-34.86%	-25.46%	-16.86%	0.96%	0.54%	1.29%
	> 30	-	64%	-0.23%	-31.13%	-24.75%	-19.80%	0.96%	0.81%	1.29%
	> 40	-	33%	0.00%	-14.30%	-8.68%	-23.73%	0.96%	1.36%	0.65%
Headway Only	-	> 7.5	47%	-0.69%	-34.25%	-37.13%	-26.27%	0.48%	0.81%	0.22%
	-	> 8.0	23%	-0.23%	-28.37%	-37.13%	-22.55%	0.96%	1.08%	1.08%
	-	> 8.5	9%	0.46%	-11.90%	-5.97%	-15.69%	1.20%	0.81%	1.29%
Load & Headway	> 15	> 7.5	42%	0.00%	-9.74%	4.69%	-15.29%	0.72%	0.27%	1.08%
	> 30	> 7.5	33%	0.00%	-14.18%	-19.63%	-19.22%	0.72%	0.54%	0.65%

Table 6-5 expresses the same results in terms of percentage change in standard deviation of travel time from the base case. Looking at the southbound and northbound standard deviations, the results show that the most dramatic reductions in travel time variability are achieved when conditional priority is based only on headway. Figure 6-7 illustrates this finding. The load-based conditional priority strategies also offer gains in terms of travel time variability reduction, but, compared to headway-based priority, the reduction in variability is gained at the cost of considerably higher priority rates.

The combination load/priority conditions seem to offer a fair reduction in blue bus travel time variability, with reductions in travel time standard deviation of up to about 20%. These benefits are not as great as conditional strategies based on headway alone, which reduce the standard deviation of southbound travel time by up to 37%. This probably because the inclusion of the load condition places a further constraint on priority eligibility and thus interferes with the headway condition's ability to achieve greater gains in travel time variability reduction. This may also explain the increase in travel time variability for the southbound buses when the load threshold is 15.

143
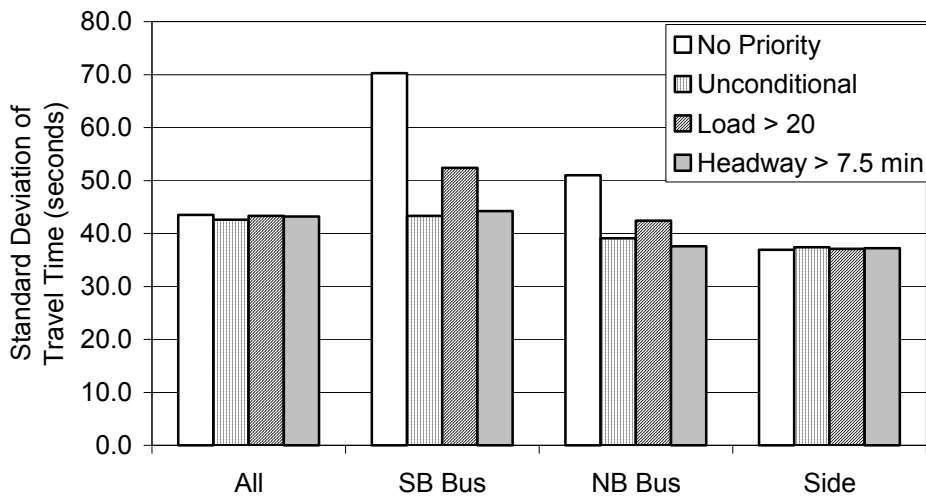
Figure 6-7: Standard deviation of travel time for vehicle types and priority strategies

6.4.3 Person Travel Time

Person travel time is a similar measure of performance to travel time. Person travel time is the total time spent by all individuals, rather than vehicles, in the network in person-hours per hour. Here, the total person travel time, rather than average person travel time, is considered by vehicle category. A topic of concern brought on by transit signal priority has been the equitable distribution of green time among individuals, as opposed to vehicles. Thus, a greater weight in the allotment of green time is generally due to transit vehicles, since vehicle occupancies are typically higher. What APTS technologies like automatic passenger counters and communications systems allow service providers to do is determine in real time whether a bus has a high enough occupancy to justify granting priority at the expense of side street signal groups. One argument in favor of load-based conditional priority is that priority is granted to the movement that has the highest potential for reducing total person travel time.

Total person travel time results are presented in Table 6-6. The percent changes in total person travel time from the base case are shown in Table 6-7. Note that person travel time for red bus passengers is considered under the "all vehicles" category, and that the average vehicle occupancy for non-transit vehicles is assumed to be 1.2 for the person travel time calculations.

144

Table 6-6: Total person travel time for various priority implementations by vehicle type

Priority Strategy	Condition(s)		Priority Rate (%)	Total Person Travel Time (person-hours/hour)						
				All Vehicles	Blue Buses			Other Vehicles		
	Load (# pass.)	Headway (minutes)			All	South-bound	North-bound	All	Side Origins	Arterial Origins
No Priority	-	-	-	290.4	46.2	25.6	20.6	203.4	105.5	97.9
Unconditional	none	none	100%	281.8	36.0	19.7	16.3	204.1	107.2	96.9
Load Only	> 20	-	76%	282.8	38.3	21.6	16.6	204.8	106.5	98.3
	> 30	-	64%	282.2	39.6	23.0	16.6	204.4	106.4	98.0
	> 40	-	33%	280.3	39.4	22.8	16.7	204.3	106.1	98.1
Headway Only	-	> 7.5	47%	282.1	39.9	22.4	17.5	204.3	106.3	98.0
	-	> 8.0	23%	283.1	40.6	23.7	16.9	204.0	106.0	98.0
	-	> 8.5	9%	286.7	42.6	24.7	17.8	203.9	105.8	98.1
Load & Headway	> 15	> 7.5	33%	282.9	41.0	24.1	16.9	204.3	105.9	98.4
	> 30	> 7.5	42%	289.8	47.6	27.5	20.1	204.2	105.9	98.2

Table 6-7: Percent change in total person travel time from base case

Priority Strategy	Condition(s)		Priority Rate (%)	% Change in Total Person Travel Time from Base Case						
				All Vehicles	Blue Buses			Other Vehicles		
	Load (# pass.)	Headway (minutes)			All	South-bound	North-bound	All	Side Origins	Arterial Origins
No Priority	-	-	-	-	-	-	-	-	-	-
Unconditional	none	none	100%	-2.95%	-21.99%	-23.10%	-20.61%	0.31%	1.54%	-1.03%
Load Only	> 20	-	76%	-2.60%	-17.10%	-15.44%	-19.15%	0.67%	0.91%	0.41%
	> 30	-	64%	-2.84%	-14.19%	-10.01%	-19.40%	0.47%	0.78%	0.11%
	> 40	-	33%	-3.47%	-14.56%	-10.95%	-19.06%	0.40%	0.57%	0.21%
Headway Only	-	> 7.5	47%	-2.85%	-13.56%	-12.39%	-15.02%	0.40%	0.72%	0.04%
	-	> 8.0	23%	-2.50%	-12.07%	-7.31%	-17.99%	0.27%	0.40%	0.12%
	-	> 8.5	9%	-1.26%	-7.80%	-3.32%	-13.37%	0.20%	0.21%	0.17%
Load & Headway	> 15	> 7.5	33%	-2.58%	-11.16%	-5.71%	-17.94%	0.43%	0.39%	0.46%
	> 30	> 7.5	42%	-0.22%	3.14%	7.66%	-2.48%	0.35%	0.37%	0.33%

The a priori expectation that load-based conditional priority strategies can offer the greatest gains in terms of total passenger throughput, greater even than unconditional strategies, is upheld by the results. The most interesting observation from Tables 6-6 and 6-7 is that the most restrictive load-based conditional priority strategy ensures the lowest system-wide total person travel time in the network. Only a third of blue buses requesting priority are granted priority when the minimum load constraint is set at 40. At first it may seem contradictory that less frequent priority would yield lower person travel times. However, by limiting the delay to side street traffic except in special cases where bus loads are very high, a pseudo-optimal compromise is reached that "minimizes" the total person travel time.

Some other expected tradeoffs can be seen in Tables 6-6 and 6-7. The greatest benefit in terms of reduced person travel time for blue bus passengers is achieved with unconditional priority, but only at a greater cost to side street movements relative to the conditional priority strategies. Similarly to the travel time results, a modest benefit accrues to non-transit vehicles with arterial origins.

Conditional priority strategies that are based on headway alone also offer gains in terms of reduced total person travel time, with the least restrictive condition (headway > 7.5 minutes) comparing most closely with the unconditional and load-only conditional strategies. The combination load/headway conditional priority strategies offer some improvements in reduced person travel time. Again, the greater benefit arises when the priority conditions are less restrictive. As expected, the combination of load and headway conditions does not yield as great an improvement in reduced person travel time as the strategies based on load alone due to the added headway constraint.

6.4.4 Headway Variability

Headway variability is probably a more direct measurement of transit service reliability, and thus passenger level of service, than travel time variability since the headways determine how long, on average, passengers wait for a bus. The new enhancements to MITSIMLab's transit representation allow the user to collect output at the bus stop level. Every time a bus arrives at a bus stop, a record is created that includes the route and the time headway since the arrival of the previous bus. From this information, one can calculate the means and standard deviations of headway by route, by bus stop, by direction and by other means of categorization. The standard deviations of time headway for blue buses (all, northbound, southbound) are provided in Table 6-8. The percent change in standard deviation of headway results are given in Table 6-9. The mean headway for all scenarios for northbound and southbound buses is consistently about 450 seconds, equal to the design headway of 7.5 minutes, or 8 buses per hour.

Table 6-8: Standard deviation of blue bus headway

Priority Strategy	Condition(s)		Priority Rate (%)		Standard Deviation of Blue Bus Headways		
	Load (# pass.)	Headway (minutes)	South-bound	North-bound	All	South-bound	North-bound
No Priority	-	-	-		63.0	78.3	42.8
Unconditional	none	none	100%	100%	37.5	43.1	30.9
Load Only	> 20	-	77%	76%	55.5	56.1	54.9
	> 30	-	66%	62%	57.2	73.5	33.7
	> 40	-	30%	37%	69.8	77.8	60.5
Headway Only	-	> 7.5	46%	48%	50.4	53.3	47.4
	-	> 8.0	27%	18%	56.2	63.0	48.5
	-	> 8.5	14%	4%	68.1	86.3	42.9
Load & Headway	> 15	> 7.5	41%	39%	65.5	86.3	33.8
	> 30	> 7.5	33%	27%	67.7	70.5	64.9

Table 6-9: Percent change in standard deviation of blue bus headway

Priority Strategy	Condition(s)		Priority Rate (%)		Percent Change in Standard Deviation of Blue Bus Headways		
	Load (# pass.)	Headway (minutes)	South-bound	North-bound	All	South-bound	North-bound
No Priority	-	-	-		-	-	-
Unconditional	none	none	100%	100%	-40.48%	-44.96%	-27.80%
Load Only	> 20	-	77%	76%	-11.90%	-28.35%	28.27%
	> 30	-	66%	62%	-9.21%	-6.13%	-21.26%
	> 40	-	30%	37%	10.79%	-0.64%	41.36%
Headway Only	-	> 7.5	46%	48%	-20.00%	-31.93%	10.75%
	-	> 8.0	27%	18%	-10.79%	-19.54%	13.32%
	-	> 8.5	14%	4%	8.10%	10.22%	0.23%
Load & Headway	> 15	> 7.5	41%	39%	3.97%	10.22%	-21.03%
	> 30	> 7.5	33%	27%	7.46%	-9.96%	51.64%

It is difficult to draw conclusions from the results in Tables 6-8 and 6-9 because the standard deviations of the headways appear to improve (reduce) as much as they degrade (increase), showing no clear or consistent trends. It is even difficult to show from the headway results that headway-based conditional priority strategies can generally serve to even out the headways along a route, since southbound headway variability tends to improve and northbound headway variability often does not. Looking at all blue buses together, however, the two least restrictive thresholds for load-only and headway-only conditional priority appear to reduce the standard deviation of headway by as much as 20%, which is expected.

The lack of an apparent pattern is probably a consequence of three factors: assumptions regarding the time headways between subsequent buses entering the network, the small size of the network, and assumptions about uniform passenger distribution along the length of the blue bus route in either direction. The input departure rate of blue buses entering the network is assumed to be constant. Since blue buses enter the network with even headways, and because the length of the route in the study network is relatively short, there is not much space or time within which to show the random deviations in headway that arise from the cumulative effect of signal delay, dwell time and congestion along the route.

The assumption regarding uniform distribution of passenger demand (i.e. equal arrival and alighting rates at all stops along the route) contributes further to this lack of random variability in bus headway. Although passenger arrivals are randomly drawn from a Poisson distribution, which leads to considerable randomness in passenger arrivals, and thus dwell times, the constant mean arrival rates at all stops do not contribute enough variation along the network to cause significant deviations from the design headway. The purpose of headway-based conditional priority strategies is to compensate for inherently random headway deviation by allowing late vehicles to catch up. The small study network, combined with simplifying assumptions, does not provide a large enough stage for the full effect of random headway deviation to materialize, thus defeating the usefulness and reliability of headway-based conditional priority simulation.

6.4.5 Increased Demand

Various ITS strategies operate well under normal operating conditions, but become unstable under conditions of increased demand. In order to ensure that various priority implementations do not afford travel time savings to blue buses only at very high costs to other modes when demand becomes high, three strategies are simulated with 30% and 40% increases in demand on Liljeholmsbron. Liljeholmsbron is the bridge that carries traffic northeast into Sodermälm during the morning peak, and is the only "side street" with enough demand to be substantially penalized by various priority implementations.

The average vehicle and total person travel times, categorized by vehicle type, are given in Table 6-10. Table 6-11 contains the percent changes in average vehicle and total person travel time from the base case (no priority, increased demand on Liljeholmsbron) under the various priority strategies. Since the benefits of headway-based (i.e. headway-only and headway/load combined) conditional priority strategies are not fully realized on the relatively small study network, a middle-range load-based conditional priority strategy is simulated to evaluate the impacts of conditional priority under increased non-priority demand on vehicle and person travel times.

Table 6-10: Average vehicle travel time for 30% and 40% increase in demand on Liljeholmsbron

Priority Implementation	Condition	Priority Rate (%)	Average Travel Time Per Vehicle (seconds)						
			All Vehicles	Blue Buses			Other Vehicles		
				All	South-bound	North-bound	All	Side Origins	Arterial Origins
130% Demand on Liljeholmsbron									
No Priority	-	-	116.4	244.5	280.5	209.0	115.8	114.1	118.2
Unconditional	none	100%	118.1	220.8	246.0	195.6	117.7	119.0	116.0
Conditional	load > 30	62%	116.7	237.5	273.7	201.8	116.2	115.7	117.0
140% Demand on Liljeholmsbron									
No Priority	-	-	120.9	263.4	320.3	206.5	120.4	122.8	117.1
Unconditional	none	100%	294.9	221.4	247.3	195.2	295.7	423.3	116.2
Conditional	load > 30	62%	128.1	230.6	261.9	199.7	127.7	134.9	117.4

Table 6-10 indicates that, with an increase in demand up to around 30% on Liljeholmsbron, unconditional priority still causes only modest deterioration in side street level of service, marked by a 5-second increase in average side street vehicle travel times and very small increase in average travel time aggregated over all vehicles. However,

149

between 30% and 40%, the increase in travel demand on Liljeholmsbron hits a critical level where unconditional priority begins to cause considerable adverse side street travel time impacts. With a 40% increase in Liljeholmsbron traffic, unconditional priority increases by more than 240%, as shown in Table 6-11.

Table 6-11: Percent change in average vehicle travel time with increased demand on Liljeholmsbron

Priority Implementation	Condition	Priority Rate (%)	% Change in Average Vehicle Travel Time						
			All Vehicles	Blue Buses			Other Vehicles		
				All	South-bound	North-bound	All	Side Origins	Arterial Origins
130% Demand on Liljeholmsbron									
No Priority	-	-	-	-	-	-	-	-	-
Unconditional	none	100%	1.5%	-9.7%	-12.3%	-6.4%	1.6%	4.3%	-1.9%
Conditional	load > 30	62%	0.3%	-2.9%	-2.4%	-3.4%	0.3%	1.4%	-1.0%
140% Demand on Liljeholmsbron									
No Priority	-	-	-	-	-	-	-	-	-
Unconditional	none	100%	143.9%	-15.9%	-22.8%	-5.5%	145.6%	244.7%	-0.8%
Conditional	load > 30	62%	6.0%	-12.5%	-18.2%	-3.3%	6.1%	9.9%	0.3%

Table 6-11 shows that conditional signal priority with only a minimum load threshold of 30 passengers can achieve nearly the same reduction in average travel time for blue buses as unconditional priority and cause only a 10% increase in average side street travel time. These results, illustrated in Figure 6-8, show a remarkable improvement in average travel time under conditional, as opposed to unconditional, priority. Furthermore, conditional priority achieves almost the same benefit in terms of reduced blue bus travel time, with travel time savings of up to 18% for southbound buses.
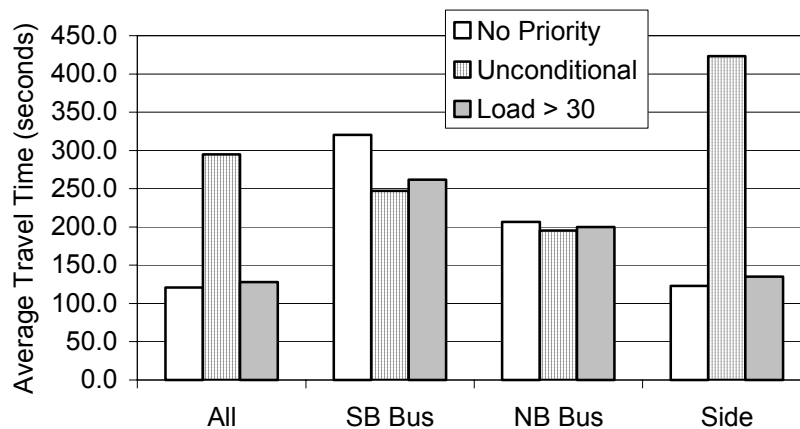

Figure 6-8: Average travel times with increased side street demand

Similar results are observed when considering total person travel time. Tables 6-12 and 6-13 show the total person travel times and the percent change in total person travel times from the base case, respectively. From the person travel time results, it can be seen that conditional priority achieves the same benefits in terms of reduced blue bus person travel time as unconditional priority, and with significantly less delay to persons on side street approaches.

Table 6-12: Total person travel time for 30% and 40% increase in demand on Liljeholmsbron

Priority Implementation	Condition	Priority Rate (%)	Total Person Travel Time (person-hours/hour)						
			All Vehicles	Blue Buses			Other Vehicles		
				All	South-bound	North-bound	All	Side Origins	Arterial Origins
130% Demand on Liljeholmsbron									
No Priority	-	-	317.0	43.5	23.9	19.6	229.9	130.6	99.3
Unconditional	none	100%	303.7	38.5	21.2	17.3	233.7	136.2	97.5
Conditional	load > 30	62%	312.8	42.1	24.5	17.6	230.7	132.4	98.4
140% Demand on Liljeholmsbron									
No Priority	-	-	329.1	47.6	27.9	19.7	246.0	147.6	98.4
Unconditional	none	100%	674.6	41.2	22.3	19.0	598.0	500.4	97.6
Conditional	load > 30	62%	338.9	40.9*	23.1	17.8	260.7	162.1	98.6

* Conditional priority is expected to yield higher total person travel time for blue bus passengers than unconditional priority. However, the difference shown here is within the acceptable error of about 1%.

Table 6-13: Percent change in total person travel time with increased demand on Liljeholmsbron

Priority Implementation	Condition	Priority Rate (%)	% Change in Total Person Travel Time						
			All Vehicles	Blue Buses			Other Vehicles		
				All	South-bound	North-bound	All	Side Origins	Arterial Origins
130% Demand on Liljeholmsbron									
No Priority	-	-	-	-	-	-	-	-	-
Unconditional	none	100%	-4.2%	-11.5%	-11.3%	-11.7%	1.7%	4.3%	-1.8%
Conditional	load > 30	62%	-1.3%	-3.2%	2.5%	-10.2%	0.3%	1.4%	-0.9%
140% Demand on Liljeholmsbron									
No Priority	-	-	-	-	-	-	-	-	-
Unconditional	none	100%	105.0%	-13.4%	-20.1%	-3.6%	143.1%	239.0%	-0.8%
Conditional	load > 30	62%	3.0%	-14.1%	-17.2%	-9.6%	6.0%	9.8%	0.2%

The demand sensitivity analysis confirms that unconditional priority can lead to dramatic increases in side street, non-priority vehicles and travelers. The results also confirm the position that conditional signal priority strategies can be used to achieve a compromise between transit travel time (both person and vehicle) benefits and side street travel time penalties.

6.4 Recommendations

The results discussed in this chapter show that conditional signal priority in general can offer comparable travel time savings to transit vehicles at a lower cost to non-transit, non-priority vehicles than unconditional priority. More specifically, load-only conditional priority can offer considerable gains in terms of reduced transit person travel time as well as, however marginal, overall gains in terms of reduced system-wide person travel time in the network. Unconditional and load-based conditional priority, however, do not offer the gains in service reliability in terms of travel time variability that headway-only conditional priority strategies can achieve. Unfortunately, further conclusions about the effects of headway-based conditional priority on service reliability in terms of headway variability could not be drawn due to the size of the network and assumptions about transit supply and demand in the network.

Varying the thresholds can also have considerable impacts on the performance measures considered in this case study. Varying any threshold, whether load or headway, in effect varies the priority strategy between two extremes: unconditional priority and no priority at all. Strict condition thresholds (e.g. high minimum load requirements and high maximum headway requirements) will lead to the scenario where priority is rarely granted, rendering the strategy ineffectual. On the other hand, very loose thresholds (e.g. low minimum load requirements and low maximum headway requirements) will lead to high priority approval rates, thus generating benefits similar to that of unconditional priority. An important conclusion from this parameter sensitivity analysis is that simulation can be an invaluable tool for determining the optimal threshold(s) for achieving a particular objective. Namely, in order to achieve maximum gains in terms of reduced total person travel time in the network, it is not necessarily beneficial to choose a lower minimum load threshold to obtain a higher priority rate. This case study demonstrates that simulation is an ideal tool for determining optimal load thresholds designed to achieve a compromise between priority for heavily loaded buses and penalties to cross street traffic. In this case study, a higher minimum load threshold yields the greatest net benefit.

Conclusions from the sensitivity analysis for headway-based conditional priority are less definitive. Since buses rarely deviate far from the design headway in the network, a lower minimum headway threshold yields the greatest benefit in terms of reduced blue bus travel time variability. At the same time, the lower headway threshold also leads to travel time savings that rival unconditional priority while interrupting the traffic signal timing to give priority only 50% of the time. While the side street traffic is not heavy enough to show substantial differences in side street travel time penalties between the different priority strategies, the lower priority rate with headway-based priority is a good indicator that headway-based conditional priority strategies compromise side street travel time performance much less so than unconditional priority.

The combination load/headway thresholds in most cases offer to a lesser degree the benefits that load-only and headway-only conditional priority strategies provide in terms of reduced person travel time and travel time variability, respectively. As expected, either threshold limits the extent to which the other may achieve its objective. For instance, a load threshold limits the extent to which the headway threshold can improve travel time variability. Furthermore, the combination conditions tend not to offer great gains in terms of travel time reduction compared with the other strategies.

When side street traffic demand is considerable, as in the case of the increased demand on Liljeholmsbron, unconditional priority can indeed have a profound impact on the delays suffered by side street vehicles and travelers. The results from the demand sensitivity analysis, however, show that conditional priority strategies can effectively allay the travel time penalty to non-priority movements while preserving transit travel time benefits.

Overall, the results from the case study, for the most part, uphold a priori expectations about the benefits and tradeoffs of various transit signal priority strategies. In the Stockholm study network considered in this research, unconditional strategies are most effective, since the penalty to side street traffic is small due to low side street demand. However, in the case that side street demand becomes more of a factor, headway-only or load-only conditional priority strategies are recommended, depending on the objective (e.g. improved transit reliability or reduced person travel time).

Chapter 7

Conclusions

7.1   Summary

The primary objective of this research is to develop a microscopic simulation laboratory for the design and evaluation of APTS applications. The motivations for such a tool include growing interest in the bus transit industry in advanced technologies, a growing need among transit service providers to improve service planning and operations in order to compete with the private automobile, and the ever-present gap between revenue and cost that has burrowed its way deep into the fabric of bus transit systems across North America. APTS is a broad concept, which encompasses a wide variety of intelligent transportation systems applications in public transit. Nevertheless, this thesis attempts to pull together the state of the art of APTS in order to develop a comprehensive set of modeling requirements that together provide the basic functionality for simulating APTS at the operational level in a microscopic simulator.

The state of the art of APTS is first reviewed in order to base the model requirements on current trends and innovation in APTS and in order to establish with which aspects of bus transit operations the various APTS interact. With a firm understanding of how various APTS technologies and applications interface with transit operations, one can deduce a set of bus transit components and features upon which APTS rely. These features and components of bus operations are thus the model requirements a simulator must represent in order to simulate APTS operations. This was

the approach to developing a set of model requirements for the development of an APTS simulation laboratory.

The requirements identified in this thesis are meant to be a starting point for developing a fully functional multimodal traffic and transit operations simulation laboratory. To this end, the following broad requirements are identified as the basic building blocks for creating an APTS simulation laboratory:

- Transit System Representation
- Transit Vehicle Movement and Interaction
- Transit Demand Representation
- APTS Representation
- Measures of Effectiveness

These requirements give the simulator the capacity to simulate the full spectrum of bus operations phenomena, from schedule reliability to bus bunching, and to capture the range of random elements that affect bus progression, including congestion, signal delay and variable passenger demand. Furthermore, these requirements allow the user to simulate interactions between various components of a multimodal urban network, including interaction between passengers and transit vehicles and between transit vehicles and other modes.

A framework was developed for incorporating the model requirements into MITSIMLab, a simulation laboratory developed for the design and testing of alternative advanced traffic management systems and advanced traveler information systems. The implementation of the model requirements in MITSIMLab expands the simulator's evaluation scope to include advanced public transportation systems. The end result is a simulation-based tool that is useful to both researchers and practitioners for designing new and innovative transit operations control and passenger information applications and for testing alternative APTS strategies prior to implementation in the field.

A case study for the evaluation of alternative conditional signal priority strategies in Stockholm, Sweden is conducted to demonstrate the usefulness of the APTS simulator. The measures of effectiveness generated by the case study simulations provide the grounds for making an informed, strategic signal priority recommendation.

7.2 Findings

A case study to evaluate alternative signal priority implementations in Stockholm is used to demonstrate the bus operations functionality in MITSIMLab. From the case study, two kinds of findings are addressed here: general findings regarding the success of the simulation tool for evaluating APTS and more specific findings regarding unconditional and conditional priority strategies.

To begin with more specific findings, some interesting conclusions may be drawn from the measures of effectiveness produced in case study. In general, the results from the case study support the rationale that conditional priority can offer transit travel time benefits on par with unconditional priority *and* at a lower cost side street traffic. This presumption is best demonstrated with the load-based conditional priority simulations, which suggest that considerable gains may be made in terms of reduced transit person travel time without causing excessive delay to side street traffic. Furthermore, with a carefully chosen threshold, load-based strategies can achieve a system-wide reduction in person travel time greater than that of unconditional priority.

The headway-based priority conditions offer reduction in travel time variability comparable to unconditional priority and with less frequent priority. The side street traffic is not great enough to show much difference between unconditional and headway-based conditional priority, but the results do suggest that headway-based conditional priority can achieve favorable benefits in terms of reliability (i.e. reduced travel time variability) without interrupting green times for side streets nearly as often. However, due to the relatively small size of the network and simplifying assumptions about initial bus headways and demand distribution, further conclusions could not be drawn from the case study in terms of headway variability.

These results suggest that passenger level of service can be improved by reducing in-vehicle travel times. However, the results also show that the most appropriate load threshold in terms of person travel time does not necessarily return the greatest benefit in terms of reduced travel time variability, and thus passenger waiting time at stops. Since load-based conditional priority accounts only for passenger load and does not consider the vehicle's position with respect to the schedule. Likewise, while headway-based

strategies yield significant benefits in terms of reduced travel time variability, the gains in reduced person travel time are not as great as those of headway-based strategies. Thus, the goal of combination load/headway based strategies is to strike a compromise between reliability and person travel time objectives. The results from the case study show, however, that the use of multiple conditions can considerably limit the magnitude of the benefits that either condition might have achieved on it's own as a single condition.

The sensitivity of various priority strategies to side street demand is not well pronounced in the Stockholm network due to the small side street traffic levels. In order to evaluate the performance of alternative priority strategies where the penalty to side street traffic is a concern, the travel demand on Liljeholmsbron is artificially inflated by 30% and 40%. The results show that, as side street demand reaches a certain level, unconditional priority can have severe consequences in terms of side street delays. However, conditional priority can lead to travel time benefits that compare favorably with unconditional priority with only a fraction of the added side street delay.

Perhaps the most important finding from the case study is that, given a realistic representation of bus operations, a simulation laboratory can be valuable means for testing and evaluating APTS. The conditional signal priority case study demonstrates the simulation of an APTS strategy that relies on schedule information, advanced passenger counting systems, and communications systems, which could not be done before the model requirements were incorporated into the model.

With the model requirements in place, MITSIMLab is especially useful for conducting important sensitivity analyses. It might be clear that load-based conditional priority can improve person throughput and that headway-based strategies can be implemented to improve transit reliability, but to what extent, with what costs, and which thresholds determine the greatest net benefit are difficult questions to answer. With an APTS simulation laboratory, these questions become manageable. Thus, the most significant finding overall from this research is that the 5 model requirements identified in this thesis are sufficient to support the simulation of complex APTS applications at the operational level.

7.3   Future Research

It is clear from this thesis that a traffic and transit simulation laboratory capable of simulating APTS can be an invaluable tool for aiding progress and innovation in APTS design.   The gaps in bus operations modeling and simulation literature encountered during the course of this thesis, however, highlight a glaring need for future research into the behaviors of bus operators and the complex interactions between modes in an urban traffic setting.   From mere observation and intuition, one can deduce that bus operators behave differently than other drivers, and that other drivers behave differently in the presence of buses.   An example of valuable new research would be an effort to calibrate and validate driver behavior models when buses are present in order to determine whether bus-following is indeed fundamentally different from regular car-following behavior.   Future research into the nature of these interactions can go a long way to determine the extent to which these interactions affect transit-specific and network measures of performance.   This kind of research is the first step toward stimulating new ideas and strategies for minimizing the adverse impacts that arise from intermodal interaction.

Another area of recommended future research is passenger behavior modeling. Presently, there is literature available regarding passenger route and mode choice.   While these research efforts are an important first step, it would be interesting to develop similar models in a simulation context and to implement such models into a microscopic simulator.   This would allow the simulation of an even broader range of APTS, namely traveler information systems.   The modeling of individual passengers with attributes and origins and destinations is outside the scope of this thesis, but is a logical progression from the work presented in this thesis toward a better and more capable APTS simulation laboratory.

Other areas of future research are those that might determine the impacts of various APTS on user choices and behaviors.   For example, it would be beneficial to estimate dwell time models when different electronic fare payment systems are present on the bus. This kind of research could yield better model input parameter for simulating microscopic bus operations.

Finally, aside from model development, another logical and important progression from this thesis is the simulation of larger, more complex bus transit networks to test the full functionality of the model requirements. Such future research should consider large transit networks that cover multiple full-length routes to capture interlining and layover activities and bus bunching. It will also be interesting to simulate time periods long enough to capture the time-varying nature of passenger demand. Simulating such cases that encompass the breadth and complexity of bus operations is critical for adding depth to the model requirements identified in this thesis and to identifying and addressing new challenges in bus operations and APTS simulation.

Appendix A

Glossary of Transit Terminology

Some definitions are useful when discussing bus transit schedules. The following is a list of some of the more common terms used to describe a bus schedule:

- **"Bus run"**: Bus run is in quotations because it has been adopted for use in this research and may not be common transit terminology. A bus run is similar to a run, but is a piece of work assigned to a single bus, rather than to a single driver.

- **Deadhead**: The movement of a vehicle from one location to another the vehicle is not in service. Deadheading is typically done to or from a terminal or depot to a location on a route.

- **Express**: To skip selected stops along a route without stopping.

- **Interline**: The transition from service of one route to service of another. A bus typically interlines when it has completed its final trip on one route and must move to another route to begin its next trip on a new route.

- **Route**: The path through the network traveled by buses and connecting all bus stops served by the route.

- **Run**: A piece of work performed by a single driver. A driver is assigned to a run, which may be a series of trips on a single route, or a series of trips and interlining trips in service of more than one route.

- **Short turn**: To turn a vehicle around and begin service of the route in the opposite direction before reaching the terminal, or endpoint of the route.

- **Trip**: A single, one-way service of the route from one endpoint to the other. When a bus travels from one end of the route to the other, it has completed a trip.

The concepts defined above, to a large extent, make up the bus transit schedule and are used to describe the assignment of a crew of bus operators and a fleet of buses to the various pieces of work defined in a schedule.

Appendix B

Sample Bus Transit Supply Input Files

Four input files were created in MITSIMLab this thesis to define the transit network, schedule and fleet assignment elements of a bus transit system. Additionaly, modifications were made to two pre-existing input files in order to enhance the flexibility with which bus operations are defined in the simulator. The four input files developed in this research include:

- Transit Network Representation File – `route.dat`
- Schedule Definition File – `schedule.dat`
- Run Definition File – `run.dat`
- Bus Assignment File – `bus.dat`

Each of these input files is described in sections A.1-A.4. The two pre-existing files that were modified are:

- Network File – `network.dat`
- Demand File – `od.dat`

The general network file, network.dat, was modified to allow the user to specify the locations and attributes of bus stops in the network. Thus, the changes to the network.dat file are described in the context of the transit network representation in section A.1. The demand input file, od.dat, has been changed to allow the user to specify the assignment of buses to frequent services, such as bus rapid transit. Therefore, the changes to od.dat are discussed in the context of bus assignment in section A.4. The hypothetical network that is used to demonstrate the sample input files in this appendix is shown in Figure B-1.
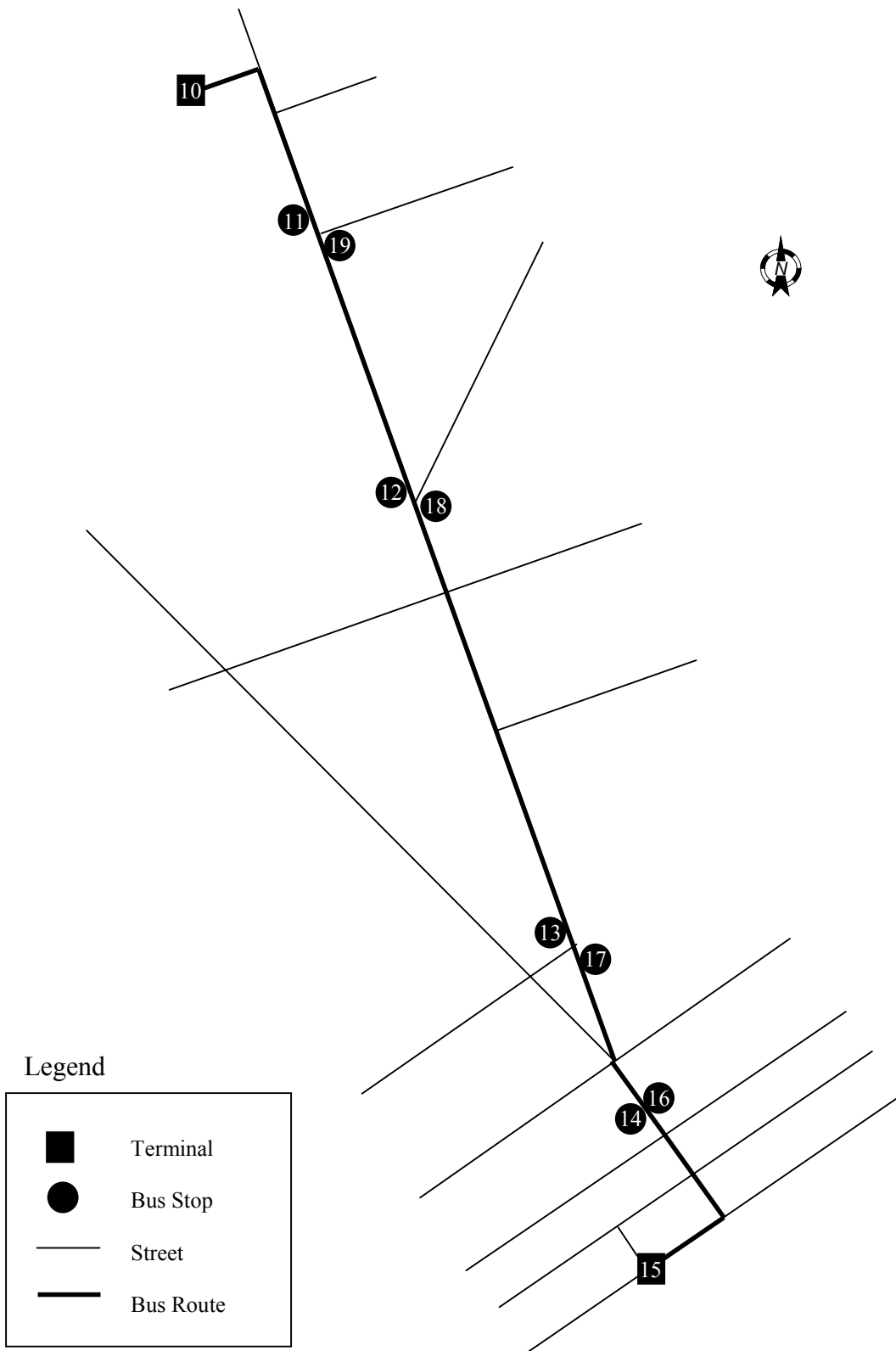
Figure B-1: Diagram of a hypothetical urban network and transit route

B.1 Transit Network Representation File

MITSIMLab represents a roadway network as a system of links and nodes. Figure B-2 shows a link-node diagram of the portion of the network used by the bus route shown in Figure B-1.

Figure B-2: Link-node diagram of transit network shown in Figure B-1

Links are defined by an upstream and a downstream node. Links may be partitioned into sub-links, called segments, where the cross-section of a segment (e.g. numbe r of lanes) is constant throughout its length. Thus, segmentation of the links allows the user to specify

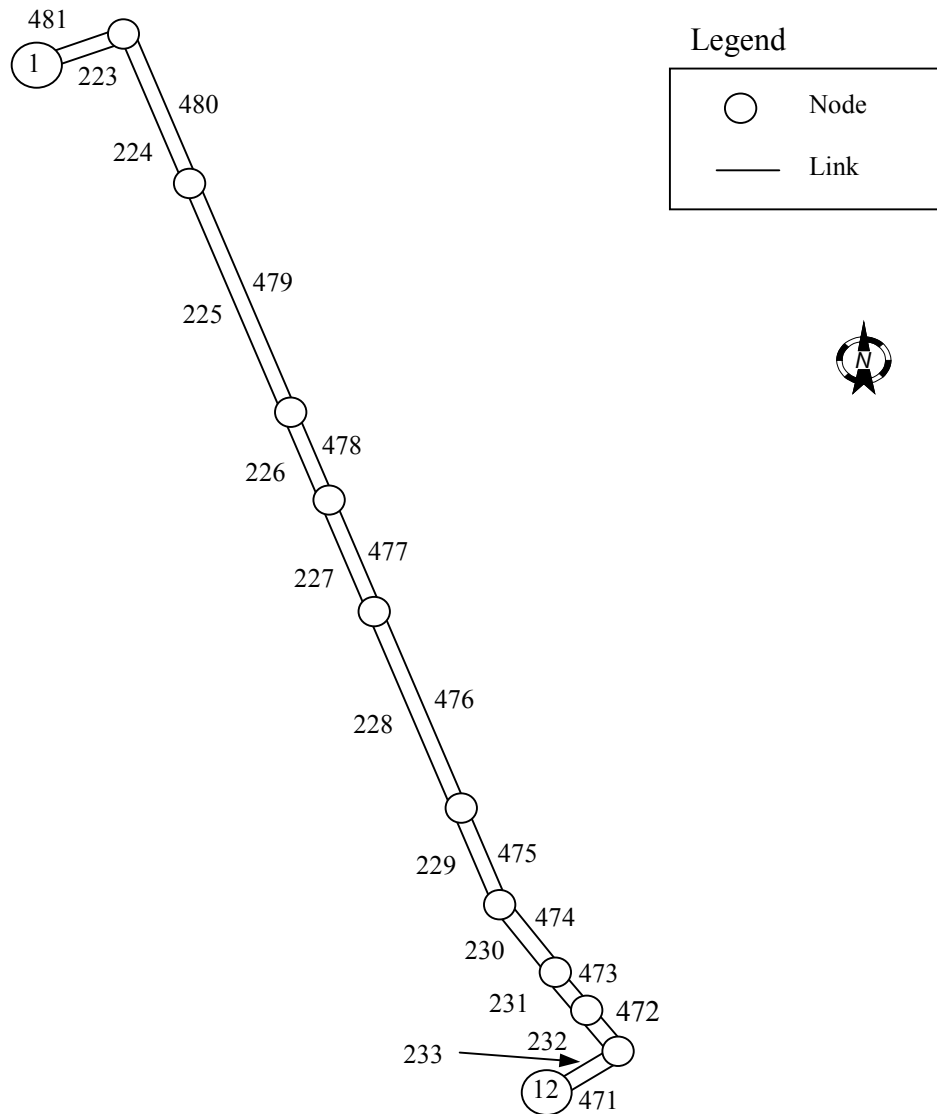varying geometries along a single link. Each segment has at least one lane. Node, lane, segment and link IDs are unique (e.g. no two lanes have the same ID, etc.). Only the beginning and ending node IDs will be relevant in this appendix, and thus the others are omitted from Figure B-2.

Point objects (e.g. loop detectors, traffic signals, toll booths, bus stops) are defined in the `network.dat` file, where the location of the device is determined by a unique segment ID and a proportion of the segment length (from the downstream end) where the device resides.   Below is a sample portion of a `network.dat` file, demonstrating how bus stops might be declared for the network in Figure B-1:

```
[Bus Stops] :
{
  {328 20 0.13
    {10 0x3 31 0 100 6 0}
  }
  {328 31 0.3
    {11 0x3 44 128 75 6 0}
  }
  {328 35 0.87
    {12 0x3 54 0 75 6 0}
  }
  {328 40 0.172
    {13 0x3 63 0 75 6 0}
  }
  {328 52 0.7
    {14 0x3 96 0 75 6 0}
  }
  {328 42 0.18
    {15 0x3 67 0 75 6 0}
  }
  {328 45 0.6
    {16 0x3 75 0 75 6 0}
  }
  {328 69 0.55
    {17 0x3 128 0 75 6 0}
  }
  {328 45 0.6
    {18 0x3 75 0 75 6 0}
  }
  {328 69 0.55
    {19 0x3 128 0 75 6 0}
  }
}
```

Visibility Distance (ft)   Segment ID   Position in Segment

Bus stop ID   Initial State   Lane ID   Lane Use Rules

Stop Length (ft)   Flow Rate (vph)   Wayside Dummy

The format for specifying bus stops is identical to that of most other control devices, including toll booths and traffic signals. Thus, some of the inputs are generic and are not

particularly relevant to bus stops. Below are a few explanations of the inputs shown above:

- Visibility distance – Visibility distance is more relevant to toll booths and traffic signals, where vehicles begin to react to the devices when they are within the object's visibility. However, bus operators alone "respond" to bus stops and move toward the bus stop when they are within the bus-to-stop visibility described in Chapter 3. Thus, the visibility distance in the `network.dat` file is not used.

- Segment ID – The ID of the segment in which the bus stop is located.

- Position in segment – The fraction of the segment length indicating the distance from the downstream endpoint of the segment where the bus stop is located.

- Bus stop ID – Unique bus stop ID.

- Initial state – The initial state is more relevant to traffic signals, where the user may specify the signal indication (e.g. red, green) at the start of the simulation.

- Lane ID – The ID of the lane in which the bus stop is located.

- Lane use rules – Lane use rules are intended for toll booth operations, where the user may specify electronic toll collection lanes, etc. The lane use rules do not pertain to bus stops.

- Stop length – The length of the bus stop, which the user may use to specify the distance upstream of the bus stop "stop line" within which a stopped bus (whether due to congestion or due to another bus already at the stop) may serve passengers and proceed.

- Flow rate – The flow rate is specific to toll booth operations, where the user may specify the rate at which vehicles may be processed by a toll booth lane.

- Wayside dummy – The wayside dummy is equal to 1 if the stop is a wayside stop, and 0 otherwise. The specification of a stop as wayside triggers certain bus operator behavior when the bus is ready to depart from the stop to merge with the adjacent traffic stream.

The general network data file (network.dat) defines the physical dimensions of the network. The transit network representation file (route.dat), on the other hand, specifies

those portions of the general network that are used by particular transit routes. Below is a sample route.dat file for the network in Figure B-1:

```
[Bus Route Table] : 2
{
{ 86
      { 223 224 225 226 227 228 229 230 231 232 233 }
      { 10   11   12   13   14   15 }
}

{ 93
      { 471 472 473 474 475 476 477 478 479 480 481 }
      { 15   16   17   18   19   10 }
}
}
```

Number of routes defined in the file

Sequence of link IDs

Sequence of bus stop IDs

Route ID

The example shown above defines the bus route shown in Figure B-1 as two routes in MITSIMLab, one southbound and one northbound. The user may also include a design headway in the definition of a route, as shown below.

```
[Bus Route Table] : 4
{
{ 86   300.0
      { 223 224 225 226 227 228 229 230 231 232 233 }
      { 10   11   12   13   14   15 }
}

{ 93   300.0
      { 471 472 473 474 475 476 477 478 479 480 481 }
      { 15   16   17   18   19   10 }
}
}
```

Design headway (sec)

Specifying a design headway is useful for defining frequent services (e.g. bus rapid transit), which do not have scheduled arrival times at stops. The design headway may be used when evaluating APTS that must determine the deviation from a desired headway in order to devise a real-time strategy for achieving a predefined level of service.

B.2 Schedule Definition File

The schedule definition file is used to define work trips to which buses may be assigned. A trip is a single, one-way, end-to-end movement along a single route. The schedule definition file allows the user to define trips with scheduled arrival times at stops along a route. Table B-1 is a hypothetical real-world schedule timetable for the route shown in Figure B-1.

Table B-1: A hypothetical bus schedule timetable

ROUTE												
9	**CROSS TOWN**											
	Southbound						Northbound					
	10	11	12	13	14	15	15	16	17	18	19	10
							6:15	6:27	6:42	6:47	6:57	7:15
							6:45	6:57	7:12	7:17	7:27	7:45
AM	6:00	6:35	6:45	6:50	7:03	7:15	7:15	7:27	7:42	7:47	7:57	8:15
	6:50	7:05	7:15	7:20	7:33	7:45	7:45	7:57	8:12	8:17	8:27	8:45
	7:20	7:35	7:45	7:50	8:03	8:15	8:15	8:27	8:42	8:47	8:57	9:15
	7:50	8:05	8:15	8:20	8:33	8:45	8:45	8:57	9:12	9:17	9:27	9:45
	8:20	8:35	8:45	8:50	9:03	9:15	9:15	9:27	9:42	9:47	9:57	10:15
	8:50	9:05	9:15	9:20	9:33	9:45	9:45	9:57	10:12	10:17	10:27	10:45
	9:20	9:35	9:45	9:50	10:03	10:15	10:15	10:27	10:42	10:47	10:57	11:15
	10:20	10:35	10:45	10:50	11:03	11:15	11:15	11:27	11:42	11:47	11:57	12:15
	11:20	11:35	11:45	11:50	12:03	12:15	12:15	12:27	12:42	12:47	12:57	1:15

The shaded portion of the AM schedule in Table B-1 is defined in the MITSIMLab input format below:

Number of trips defined in the file

```
[Bus Schedule Table] : 9
{                                           Sequence of arrival times
{ 86                  Trip IDs
  186  { 00:06:00   00:06:35   00:06:45   00:06:50   00:07:03   00:07:15 }
  286  { 00:06:50   00:07:05   00:07:15   00:07:20   00:07:33   00:07:45 }
  386  { 00:07:20   00:07:35   00:07:45   00:07:50   00:08:03   00:08:15 }
  486  { 00:07:50   00:08:05   00:08:15   00:08:20   00:08:33   00:08:45 }
  586  { 00:08:20   00:08:35   00:08:45   00:08:50   00:09:03   00:09:15 }
  686  { 00:08:50   00:09:05   00:09:15   00:09:20   00:09:33   00:09:45 }
  786  { 00:09:20   00:09:35   00:09:45   00:09:50   00:10:03   00:10:15 }
  886  { 00:10:20   00:10:35   00:10:45   00:10:50   00:11:03   00:11:15 }
  986  { 00:11:20   00:11:35   00:11:45   00:11:50   00:12:03   00:12:15 }
        { 10   11   12   13   14   15 }
}
```

Route ID

Sequence of bus stop IDs

The schedule input can be specified in a number of ways to define various types of services. The sequence of bus stop IDs is optional. If no bus stop IDs are specified, then the buses that serve those trip IDs will stop at the bus stops that are specified in the route input in the transit network representation file. The user may also give a reduced set of bus stop IDs in order to define express services that only serve certain stops. For example, if, from 8:20 AM onward (i.e. trips 586-986), the southbound trips are assigned to an express service that includes only stops 10, 11, 14, and 15, the input may be specified like so:

```
[Bus Schedule Table] : 9
{
{ 86
  186   { 00:06:00   00:06:35   00:06:45   00:06:50   00:07:03   00:07:15 }
  286   { 00:06:50   00:07:05   00:07:15   00:07:20   00:07:33   00:07:45 }
  386   { 00:07:20   00:07:35   00:07:45   00:07:50   00:08:03   00:08:15 }
  486   { 00:07:50   00:08:05   00:08:15   00:08:20   00:08:33   00:08:45 }
}
{ 86
  586   { 00:08:20   00:08:35   00:09:03   00:09:15 }
  686   { 00:08:50   00:09:05   00:09:33   00:09:45 }
  786   { 00:09:20   00:09:35   00:10:03   00:10:15 }
  886   { 00:10:20   00:10:35   00:11:03   00:11:15 }
  986   { 00:11:20   00:11:35   00:12:03   00:12:15 }
        { 10   11   14   15 }
}
```

Trips 186 to 486 serve all routes on the stop, so no bus stop IDs were specified. The schedule definition input file may also look very different if frequent services are defined. In order to specify trips that have no scheduled input files, the user need only specify a trip ID and a route ID. For example, if the route shown in Figure B-1 were a bus rapid transit route with no scheduled arrival times, the schedule input file may be defined as shown below:

```
[Bus Schedule Table] : 2
{
{ 86 186 }
{ 93 193 }
}
```

Since there are no scheduled arrival times, which distinguish one trip from another, only a trip ID and a route ID are required. Thus all southbound buses on the route may be assigned to trip ID 186, and all northbound buses to trip ID 193.

168

B.3 Run Definition File

A run in MITSIMLab is a sequence of trips, defined in the schedule definition file described in section A.2, to which a bus may be assigned. Figure B-3 highlights a sequence of alternating southbound and northbound trips from Table B-1.

ROUTE 9	RIO GRANDE										
	Southbound						**Northbound**					
	10	11	12	13	14	15	15	16	17	18	19	10
							6:15	6:27	6:42	6:47	6:57	7:15
							6:45	6:57	7:12	7:17	7:27	7:45
	6:00	**6:35**	**6:45**	**6:50**	**7:03**	**7:15**	**7:15**	**7:27**	**7:42**	**7:47**	**7:57**	**8:15**
AM	6:50	7:05	7:15	7:20	7:33	7:45	7:45	7:57	8:12	8:17	8:27	8:45
	7:20	7:35	7:45	7:50	8:03	8:15	8:15	8:27	8:42	8:47	8:57	9:15
	7:50	8:05	8:15	8:20	8:33	8:45	8:45	8:57	9:12	9:17	9:27	9:45
	8:20	**8:35**	**8:45**	**8:50**	**9:03**	**9:15**	**9:15**	**9:27**	**9:42**	**9:47**	**9:57**	**10:15**
	8:50	9:05	9:15	9:20	9:33	9:45	9:45	9:57	10:12	10:17	10:27	10:45
	9:20	9:35	9:45	9:50	10:03	10:15	10:15	10:27	10:42	10:47	10:57	11:15
	10:20	**10:35**	**10:45**	**10:50**	**11:03**	**11:15**	**11:15**	**11:27**	**11:42**	**11:47**	**11:57**	**12:15**
	11:20	11:35	11:45	11:50	12:03	12:15	12:15	12:27	12:42	12:47	12:57	1:15

Trip 186, Trip 586, Trip 886, Trip 393, Trip 793, Trip 1093

Figure B-3: Defining a MITSIMLab bus run from a real-world schedule

The run example in Figure B-3 is a relatively short run assignment for a bus, with only three round trips on the route and a time span of merely 4 hours and 15 minutes. Nonetheless, the run is used here to demonstrate run definition in MITSIMLab. The sample input file below defines two bus runs from the schedule in Table B-1 on the route in Figure B-1.
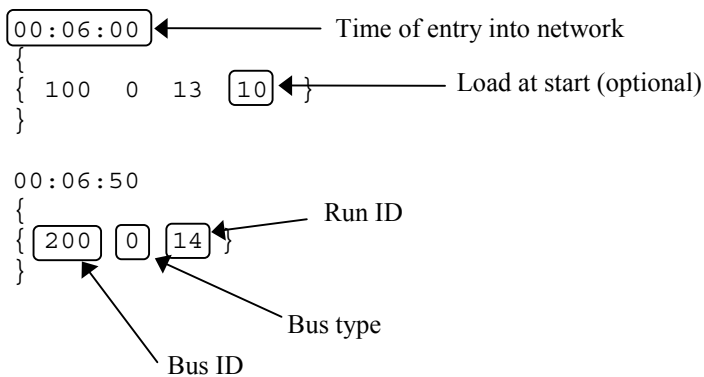
```
[Bus Schedule Table] : 2
{
{ 13  {  186   393   586   793   886   1093 }
{ 14  {  286   493   686   893   986   1193 }
}
```

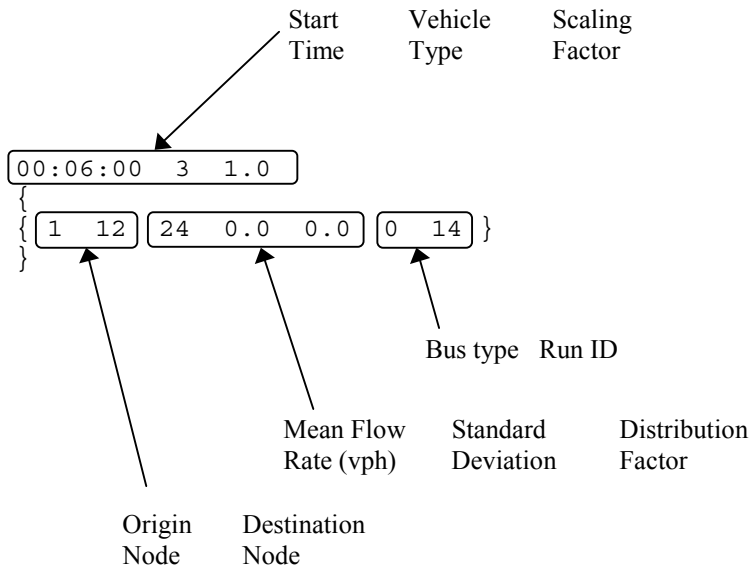Run ID

Sequence of trip (schedule) IDs

B.4 Bus Assignment File

The bus assignment file is used to assign buses to bus runs and to specify when those buses enter the network. The bus assignment file specifies a start time, the ID of the bus, the run ID to which the bus is assigned, and the bus type. The bus assignment file also gives the user the option to specify the passenger load on the bus when the bus first enters the simulation. An example of a bus assignment file is given below:

```
00:06:00    ◄───────────────  Time of entry into network
{
{  100   0   13   10 ◄─}─────────  Load at start (optional)
}

00:06:50
{                          ┌─── Run ID
{ 200   0   14 ◄────┘
}
        │     │
        │     └──── Bus type
        └──── Bus ID
```

Both buses are of type 0. A bus' type has a number of characteristics associated with it, which are specified in MITSIMLab's parameter input file, `paralib.dat`, described in Appendix D.

Specifying each individual bus assignment in the assignment input file as shown above can become cumbersome when frequent services are involved that may all be assigned to the same run ID (i.e. no scheduled arrival times). Thus, MITSIMLab offers a second option for specifying bus assignments. Bus assignments may also be specified in MITSIMLab's original demand file, `od.dat`, where the user may specify the origin (i.e. the upstream node of the first link on the first trip), the destination (i.e. the downstream node of the last link on the final trip), the flow rate (vehicles per hour), the variance of the time headway, the distribution, the bus type and the run ID. Below is an example portion of an `od.dat` file that assigns buses to the runs defined in section A.3 at an average headway of 5 minutes (i.e. 12 vph):

Start Vehicle Scaling
Time Type Factor

```
00:06:00   3   1.0
{
{ 1   12 } { 24   0.0   0.0 } { 0   14 } }
}
```

Bus type   Run ID

Mean Flow   Standard   Distribution
Rate (vph)   Deviation   Factor

Origin   Destination
Node   Node

According to the input specification above, the flow rate of 24 buses per hour begins at 6 A.M. Thus, at a mean time headway of of 2.5 minutes (24 vehicles per hour), buses of type 3 will be generated in the network. The scaling factor, 1.0 in the example above, is multiplied by the flow rates of the O-D flows enclosed in the brackets that follow the specified time period. The scaling factor is typically used for general traffic demand to test the effects of reduced and/or increased demand on the traffic management system under evaluation.

In the example above, the time headway between each bus generated to serve run 14 is, on average, 2.5 minutes. However, the user may vary the distribution of the time between successive departures by specifying the standard deviation of the departure rate and a distribution factor. The standard deviation of the average departure rate represents the randomness of the headway between successive vehicles in the O-D pair. The departure rate in MITSIMLab is determined according to a normal distribution based on the mean flow rate and its standard deviation. The distribution factor, which is a value between 0 and 1, determines the percentage of vehicles departing randomly. For example, a distribution factor of 0.4 indicates that 40% of vehicles will depart according to a Poisson distribution and the remaining 60% of vehicles will depart at constant headways. In the example above, the buses enter the network at constant headways and there is no error in the mean flow rate.

Appendix C

Passenger Demand Representation Input File

A single file is used to specify the time-varying, stop-based and route-based distribution of passengers in MITSIMLab. The demand input file, `passenger.dat`, is used to define the arrival and alighting rates of passengers at each stop in the network by route and time of day. A sample `passenger.dat` file is given below:

```
00:06:00  ◄──────────────── Start time
{
  10   { 86   25.0   0.20 }  ⎫
       { 93   50.0   0.20 }  ⎬  Two bus routes (86, 93) serve stop 10
  11   { 86   40.0   0.15 }  ⎭
       { 93   30.0   0.15 }
  12   { 86   20.0   0.10 }
       { 93   10.0   0.10 }
  13   { 86   35.0   0.05 }
       { 93   50.0   0.10 }
  14   { 86   25.0   0.05 }
       { 93   25.0   0.05 }
  15   { 86   15.0   0.25 }
       { 93   45.0   0.10 }
  16   { 86   40.0   0.05 }
       { 93   20.0   0.15 }
  17   { 86   30.0   0.10 }
       { 93   65.0   0.10 }
  18   { 86   10.0   0.15 }
       { 93   10.0   0.15 }
  19   { 86   20.0   0.20 }
       { 93   35.0   0.20 }     Bus stop ID
}

00:07:30
{
  10   { 86   80.0   0.15 }
       { 93   50.0   0.15 }       Route      Arrival           Alighting
  11   { 86   60.0   0.20 }       ID         Rate (pass/hr)    Fraction
       { 93   90.0   0.05 }
  12   { 86   85.0   0.10 }
       { 93   55.0   0.15 }
  13   { 86   65.0   0.20 }
       { 93   40.0   0.15 }
  14   { 86   45.0   0.05 }
       { 93   60.0   0.05 }
  15   { 86   70.0   0.10 }
```

172

```
       { 93   35.0   0.15 }
  16   { 86   75.0   0.25 }
       { 93   25.0   0.20 }
  17   { 86   15.0   0.15 }
       { 93   45.0   0.20 }
  18   { 86   55.0   0.20 }
       { 93   60.0   0.10 }
  19   { 86   55.0   0.10 }
       { 93   50.0   0.15 }
}
```

The example above specifies an array of arrival rates and alighting percentages for the period preceding the peak, which begins at 7:30 AM, and a new array of parameters that become active at 7:30 AM, to reflect the variation in passenger demand with time. Within a given time period, and for a given bus stop and route, the user may specify a mean passenger arrival rate for passengers wishing to board at the stop and the fraction of the passenger load on the bus that wishes to alight at the stop.

Appendix D

Parameter Input File: Bus Types and Dwell Time Parameters

Since the physical characteristics of a bus can affect bus operational performance, MITSIMLab allows the user to specify a fleet of buses that may have varying characteristics that are specific to bus operations. Below are a few examples of how bus equipment and technology can affect operations:

- Buses with low floors may have higher average boarding and alighting rates than others.

- Articulated buses with many doors available for boarding and alighting may have higher average boarding and alighting rates than standard, single-door buses.

- Prepaid fare collection strategies or electronic fare payment technologies may cause higher average boarding and alighting rates than other methods of fare collection.

- Some buses may be equipped with communications technologies that make its performance data available to other parts of the transit system.

- Different buses may have different seating and total capacities, which will affect passenger service.

Specifying more than one bus type can serve more than one purposes. First, various operational parameters, such as mean passenger boarding and alighting rates, may be specified for buses that have different configurations that affect operations differently. Second, it may be useful to specify different types of buses in order to distinguish between buses that are treated differently (e.g. some are eligible for signal priority and some are not). Bus types and corresponding parameters may be defined in MITSIMLab's parameter file, `paralib.dat`, like so:

```
# BUS ATTRIBUTES

%    (1) Label (Type)
%    (2) Length (overrides lengths in Vehicle Classes) (ft)
%    (3) Seating capacity
%    (4) Total capacity
%    (5) Average boarding rate (sec/passenger)
%    (6) Average alighting rate (sec/passenger)
%    (7) Dead time lower bound at bus stop (sec)
%    (8) Dead time upper bound at bus stop (sec)
%    (9) Crowding factor (sec/passenger)

[Bus Classes] =
{
%    1                    2    3     4     5     6     7     8     9
     "Standard Bus"      40   32    70   2.6   1.7   2.0   5.0   0.5
     "Articulated Bus"   60   46   124   2.2   1.4   2.0   5.0   0.5
}
```

The dead time can be a function of the door technology on the bus. However, the dead time can also vary from operator to operator. To represent this inherent variability, the dead time is randomly generated between the lower and upper bound specified for each bus type. The crowding factor can also vary by bus type, since the door width and number of doors used to board and alight passengers affect the congestion and subsequent delay that arises between entering and exiting passenger streams.

Appendix E

Signal Priority Input File

The signal priority input file allows the user to define the thresholds that are the basis for determining whether priority shall be granted to an approaching bus. The conditions specified in the signal priority file, `priority.dat`, can be designated to a specific route so that only buses serving a particular route may be considered for priority. The conditions may also vary by time of day, so that either the value of the thresholds or the very availability of priority may change with time. MITSIMLab is able to support five types of conditional signal priority: signal priority that depends on

- load,
- headway,
- schedule adherence,
- load and headway,
- and load and schedule adherence.

The combinations of conditions listed above are checked when a bus is detected on the approach to a signal where priority is implemented. The combination of conditions is identified in the priority input file by a condition code, which are defined as follows:

Table E-1: Condition codes and corresponding thresholds

Condition Code	Threshold(s)
0	Unconditional
1	Minimum load
2	Maximum schedule deviation
3	Maximum headway
4	Minimum load & maximum schedule deviation
5	Minimum load & maximum headway

Below is a sample `priority.dat` file that specifies each of the types of conditions shown in Table E-1.

```
06:00:00                    ─── Start time
{
    1   {  20  }  {  86    93    44    59  }
}                                              ─── Array of bus routes to which the
                                                    condition applies

08:00:00
{
    2   {  -30.0  }  {  86    93  }            ─── Threshold (minimum bus load)
    3   {  330.0  }  {  44    59  }
}                                              ─── Condition code (0 = load only)

10:00:00
{
    4   {  20 -30.0  }  {  86    93  }
    5   {  20 330.0  }  {  44    59  }
}

<END>
```

The first condition, which is valid from 6 AM until 8 AM, applies to routes 86, 93, 44 and 59 and requires only that an approaching bus have at least 20 passengers on board in order to be granted priority. The first condition under 8 AM says that a bus on either route 86 or 93 must be behind schedule by 30 seconds or more in order to qualify for priority. The second condition under 8 AM says that the headway between the subject bus and the one that preceded it must be greater than 330 seconds in order to satisfy the priority condition. After 10 AM, both conditions must be met in order to be granted priority. The headway conditions generally apply to frequent services where a desired headway is specified, but may also apply to routes with scheduled arrival times. The schedule deviation condition, however, should be used only with services with scheduled arrival times.

The user may also define the routes to which *unconditional* priority should be granted. The user may specify unconditional priority by omitting the conditions, as shown below:

```
08:00:00
{
    0   {  }   {  86    93    44    59  }
}
```

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