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Mesoscopic Simulation for Transit Operations

by

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Abstract

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The objective of this thesis is to develop a mesoscopic transit simulation model designed to support evaluation of operations planning and control, especially in the context of APTS. Examples of potential applications include frequency determination and evaluation of real time control strategies for schedule maintenance. The transit simulation model has been completely integrated into the platform of Mezzo, a mesoscopic traffic simulation model. The developed simulation, Bus Mezzo, represents boarding and alighting processes, dwell time, passengers left behind, schedule, driving roster, recovery time and trip chaining.
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Oded Cats
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Abstract

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The capabilities of BusMezzo as an evaluation tool of transit operations and control are demonstrated through case study. The application included the implementation of holding control strategies on various scenarios on a real-world high-demand line in the Tel Aviv metropolitan area.

Notations

A_{ijk} - Number of alighting passengers from line i at stop j on trip k

B_{ijk} - Number of boarding passengers on line i at stop j on trip k

λ_{ijk} - Arrival rate of passengers at stop j for line i on trip k

O_{ijk} - Occupancy on line i on arrival at stop j on trip k

h_{ijk} - Headway, time since the preceding bus (on trip $k-1$) to trip k on line i stopped at stop j

P_{ij} - The probability that a passenger on line i will get off the bus at stop j

DT_{ijk} - Dwell time for line i at stop j on trip k

δ_j^{bay} - Dummy variable indicating if the bus stop is on a bay

δ_{ijk}^{full} - Dummy variable indicating if the bus stop is fully occupied

$\delta_{ijk}^{crowded}$ - Dummy variable indicating if the bus vehicle is crowded

ET_{vk} - Actual departure time for trip k by vehicle v

ST_{vk} - Scheduled departure time for trip k by vehicle v

AT_{ijk} - Actual arrival time for line i on trip k at stop j

$RT_{\min}$ - Minimal recovery time between trips

T_l - Travel time on link l

s_{ij} - Slack size for line i at stop j

H_i - Planned headway for line i

Chapter 1: Introduction

Our world is under continuous development and advancement. People and goods can travel easier and faster and as a result, they travel more than they ever did. The steady growth in population, motorization and demand causes great traffic problems, mainly in large metropolitan areas. Until recently, transport authorities tried to cope with the increase in demand by increasing the supply, i.e. expanding the capacity of the transport infrastructures. However, this approach is not sustainable, because of the negative implications on the environment (land resources and air quality, in particular) and quality of life.

Therefore, we witness a shift in trend in recent years towards both a more efficient utilization of the transport infrastructure and effective demand management. This trend includes an emphasis on advancement of pubic transport service. In Israel, for example, 46% of the 1 billion dollars that were invested in land-transport in 1999 were spent on public transport (including intercity trains). In 2005 however, the total investment was doubled and the distribution shifted to 57% in public transport (NTA, 2006). An important challenge facing transport policy makers and planners is to design attractive alternatives to the private car, in terms of door-to-door time, reliability, and comfort, and at the same time minimize operating costs. The importance of improved public transport services and management for the creation of sustainable and efficient transport systems is well recognized (Schrank and Lomax, 2005).

An important group of tools aimed to maximize the traffic potential of an existing transport network is Intelligent Transport Systems (ITS). These tools enable data collection, real-time control strategies and performance monitoring. ITS are based on various sensing technologies such as Global Positioning System (GPS) and on communication systems that send information either to the driver or to the Transport Management Centre (TMC). ITS includes a wide range of implementations, among them electronic payment, traveller information, freeway management and collision avoidance systems.

One of the results of the development of public transport systems is that they are increasingly complex, incorporating diverse travel modes and services. The need to integrate and efficiently operate these systems poses a challenge to planners and operators. As a result, various Advanced Public Transport Systems (APTS) designed to assist operators are being developed and implemented. Advanced Public Transport Systems (APTS) are a subset of ITS, aimed to improve the level of service and operations of transit networks. APTS are generally classified into four categories of systems: fleet management, traveller information, electronic payment, and demand management. An example of APTS application is wayside transit information systems based on Automatic Vehicle Location (AVL) systems, which provide passengers with real-time departure information (FHA and FTA, 2000). The implementation of AVL systems also supports applications of various schedule monitoring techniques (such as holding, skipping and dispatching decisions) and bus priority at traffic signals. The Federal Transit Administration (FTA, 2000) reports that APTS implementation increased by over 70% between 1995 and 2000. The intensified adoption of APTS calls for methods that will represent their operation and passengers' response to them in order to evaluate them and refine their design.

There are diverse methods and tools aimed to support public transport's agencies decisions regarding routes, time tables and vehicle's schedule. This set includes passengers' surveys, land-use models, field tests, heuristics, operations research techniques and computer simulations. As new technologies and applications are proposed, tools to assist in their development and evaluation prior to field implementation are needed. However, because of the nature of public transport systems in general, and with the implementation of APTS in particular, in terms of size, complexity and dynamics, it is unrealistic to generate global analytical models.

In the context of general traffic operations, simulation models have been established as the primary tool for evaluation at the operational level (e.g. road geometry and traffic control design). Recently, they have also been extensively used to represent and evaluate various Intelligent Transport Systems (ITS), while static tools are incapable to capture their dynamics. In addition, computer simulations offer a feasible, flexible and attractive tool for planning and analysis transit systems. Transit simulations give continues perspective on transit operations, enable to compare various scenarios and represent complex interactions between the network's components: general traffic, buses and passengers. Transit simulations may serve several interests (Meignan et al., 2007): global observation of the network to check its functioning and design; evaluation and control of dynamic processes (e.g. transfers synchronization); evaluation of the network efficiency using various measures for different alternatives (e.g. routes or frequencies). However, although simulation models can have many advantages for public transport research, there has not been much effort in the development of transit simulation models.

Traffic simulations are classified into three classes, according to their level of detail and aggregation: Macroscopic, Microscopic and Mesoscopic. *Macroscopic* models represent traffic at the highest aggregate level: traffic is based on a flow-density function without representation of lanes or vehicles. At the other extreme, *Microscopic* models represent traffic at the most detailed level: individual vehicles are represented and their behaviour depends on their interactions with other vehicles, geometry, lanes assignment etc. As a result of CPU constraints, there is an inverse proportionality between the level of details and the possible size of networks under study. A third group of models exists on this scale, *Mesoscopic* models, which represent individual vehicles but avoid detailed modelling of their second-by-second movement.

A simulator capable of representing public transport system (especially with APTS applications) requires several, possibly contradicting properties: On one hand a detailed representation is needed because of the nature of the application (e.g. passenger boarding process or bus exclusive lanes), on the other hand it is essential that the simulation model would be able to represent large scale metropolitan networks, in order to evaluate the performance of public transport at a system level. Given the requirements outlined above, mesoscopic traffic simulation seems the suitable platform for transit operation and APTS evaluation.

Algers et al. (1997) surveyed 32 micro-simulations model. According to their findings, most models focus on traffic conditions: queues dynamics, weaving and the influence of accidents. On the other hand, only 52% of the micro-simulations model public transport and only 26% produce transit related outputs. While about third-fourths of the simulations evaluate vehicle detectors and adaptive traffic signals, only 42% represents priority to public transport vehicles and merely 6% models public transport information. Nevertheless, survey on users' requirements reveals that after incidents, public transport is the most important objective to be included in the simulation. In addition, 83% ranked priority to public transport vehicles as a crucial or important ITS application to be assessed. The researches concluded that micro-simulations are not useful for applications in the scale of a city because of the unnecessary level of details and the lack of transit modelling. However, it should be noted, that microscopic simulation had been improved significantly in recent years.

Later on, Boxill and Yu (2000) examined the suitability of several traffic simulation models to evaluate ITS implementations. The meta-analysis found that none of the models posses all the requirements of the application. They found that only few microscopic models simulate well local influences of APTS applications such as transit signal priority and HOV lanes. Moreover, none can be effectively used to simulate large networks. Noticeably, none of the mesoscopic models reviewed had neither a transit simulation component nor suitability to simulate ITS.

The objective of this research is to develop a mesoscopic transit simulation model designed to support evaluation of operations planning and control, especially in the context of APTS. Examples of potential applications include frequency determination, evaluation of real time control strategies for schedule maintenance and restoration from major disruptions. The development of a transit simulation has been done within the platform of the mesoscopic traffic simulation model Mezzo (Burghout 2004).

The thesis outline is as follows: Chapter 2 is a review of the transit simulations research. Then, Mezzo, the mesoscopic traffic simulator that is used as a platform for the development of the transit simulator is briefly described in Chapter 3 as well as the overall structure and implementation details of the transit simulator. The application of the transit simulator is demonstrated in chapters 4 and 5 with case study of real time control strategies on a high-demand transit line in the Tel-Aviv metropolitan area. Finally, a discussion and concluding remarks are presented on chapter 6.

Chapter 2: Literature Review

2.1 Introduction

The previous chapter described the growing need for a large-scale transit simulation and the dynamic and complex nature of current transit networks. This chapter reviews the relevant literature in the transit simulation models field. Studies concerning the characteristics of the main transit mechanisms are described in Section 3.4. In addition, the literature review for the case study on holding strategies, which concentrates on various methods to determine the variables of holding strategies, is presented in section 5.2.

The focus in the following literature review is on transit simulation design methods and simulation model characteristics and capabilities rather than the specific transit operational implications. Therefore, this review focuses on studies that contributed to the transit simulations body of knowledge and does not cover works that only used a transit simulation as a design or evaluation tool (e.g. Kim and Rilett, 2005).

There are several possible criteria to classify transit simulation studies: level of detail, main focus and level of integration. Classification by level of details will sort studies according to their simulation tool: microscopic, mesoscopic or macroscopic. Classification based on main focus will sort it according to the question: what is the main interest of the simulation model- the demand side (e.g. passenger behaviour) or the supply side (e.g. driving roster).

It is also useful to distinguish between three integration levels of transit representation into the traffic simulation as evident in the literature (note that not always there is a clear cut). The suggested classification is as follows:

1. *Adjustments:* Simulation models that do not represent transit operations and therefore require external adjustments or manipulations in order to capture some basic transit-related operations. These ad-hoc strategies try to overcome the lack of transit representation.
2. *Enhancements:* Simulation models that did not represent transit operation explicitly or modelled it on a basic level of representation and were enhanced in order to model the specific transit attributes in the matter research. Most of this researches code transit-related elements in the Application Programming Interface (API), outside of the base software.
3. *Developments:* Simulation models that were developed to model transit operations or fully integrated transit representation into the simulation.

As the transit attributes are more integrated into the model, so the model allows a better representation of the public transport, effective transit-related outputs and less inclined to human errors.

The literature review regarding transit simulation models is made up of four parts. Sections 2.2-2.4 reviews adjustment, enhancement and development transit simulation studies, respectively. Some final conclusions from the literature review are pointed out in Section 2.5.

2.2 Adjustments

At the lowest level of transit integration, the adjustment approach was taken in a couple of reviewed studies. These studies used traffic simulation models that do not represent transit operations and use it as is with external manipulations.

Khasnabis et al. (1997) used NETSIM, a general microscopic traffic simulation model typically used for evaluation of traffic control and geometric design, to evaluate the effects of several bus signal priority strategies in a 3 km transit corridor. Although the study focus was on transit, the NETSIM simulation did not produce any bus-related measure of effectiveness. Since NETSIM can not represent bus pre-emption explicitly, the animated graphic was used. Buses were tracked visually by using the graphic interface, instead of been implemented in the simulation code, and the pre-emption strategies were implemented according to the bus track as animated.

Chang et al. (2003) were also interested in comparison of various transit signal priority strategies. They used INTEGRATION- a mesoscopic traffic simulation model, which includes a signal priority feature with vehicle-class sensitivity, but has a limited modelling with regards to transit operations. This drawback led the authors to use simplified assumptions, for example: a uniform dwell time at each stop. The authors chose the adjustment approach to overtake the lack of real-time conditional priority application in INTEGRATION. They used the class-based priority mechanisms – firstly, an initial run identified the buses that were eligible for priority according to their lateness; secondly, those buses were reclassified as the priority class vehicle type for an additional simulation execution.

Since this approach requires no development efforts, it is very simple and easy to implement. However, since it does not represent transit explicitly, there are no transit passengers, stops, unique vehicles etc. Therefore, it has a very limited scope of applications, low accuracy and implication capability.

2.3 Enhancements

Enhancements studies were conducted in order to enable specific applications. The researchers modified or extended existing traffic simulation model for their purposes. This intermediate approach includes a wide spectrum of integration levels: from completely external and separated transit sub-model (API) to internal partial modifications.

Ding et al. (2001) enhanced some transit features in CORSIM, a microscopic simulator which can simulate traffic and transit operations on corridors. They included a dwell time function that depends on the numbers of boarding and alighting passengers and the headway between the buses, instead of the default function that draws dwell time from selected distribution generator. The alighting process was determined by the stop-to-stop OD time-dependent demand rates matrix and the current number of on-board passengers. In addition, they introduced time-point stops and transit vehicle types with properties as the average service time per boarding and alighting passenger and velocity-acceleration profile attributes. However, there was no treatment of the fleet's operations. The authors calibrated the transit simulator by comparison with data from a segment of a single bus route in New Jersey.

Other enhancement efforts were aimed to evaluate transit priority means. Liu et al. (1999) enhanced the microscopic simulation model DRACULA. The transit modelling did not include the representation of schedules (arrival and departure times at each stop), where buses were generated according to the service frequency. Passenger arrival rate was drawn from a normal distribution with a stop-specific average value and a fixed variance. The dwell time was a function of the number of boarding passengers only. The authors were interested in the evaluation of the following transit features: roadside vs. bay stops, reserved bus lanes vs. guide ways (special ways for guided buses) and bus signal priority. The test network included two junctions with a bus service along an artificial corridor and concentrated on the interactions between vehicles. Although DRACULA includes a learning model for the route choice, the study assumed fixed route choice and modal split.

As Bus Rapid Transit (BRT) systems gain popularity, Werf (2005) presented SmartBRT, a microscopic simulation model aimed to evaluate their performance. The model was developed as an extension of PARAMICS using its API. The level of transit integration was rather low since the SmartBRT entities, including bus stops and passengers, did not interact directly with PARAMICS entities. This created considerable complications and inaccuracies in transit modelling. For example, lane restrictions and speed controls were used in order to force buses (which PARAMICS considered to be ordinary heavy vehicles) to stop at bus stops. The model has the capability to represent bus signal priority, fare collection mechanisms and incorporates a detailed dwell time function. The detailed nature of SmartBRT is an advantage when considering a single corridor but a major drawback if a system level analysis is needed.

Another extension of PARAMICS was developed by Cortes et al. (2007). They developed MISTRANSIT (Microscopic Simulation Transit), an API using PARAMICS as a simulation platform. In general, the movement of the buses is run by PARAMICS, while MISTRANIT operates control strategies and stores transit statistics. Two additional characteristics were added to transit vehicles compared to general vehicles: the number and the function of the doors and the vehicle capacity and occupancy. These characteristics are involved in the dwell time function, as well as the numbers of boarding and alighting passengers. Most noticeably, passengers are represented individually with OD pair in terms of stops, arrival time, bus lines sequence and transference parameters (boarding, alighting and walking), while passenger assignment is determined externally. The authors conducted five experimental examples, demonstrating the MISTRANSIT modelling capabilities: on-line holding strategies, operation of bus stops nearby traffic signals, bus signal priority, capacity of bus way with skip-stop operations and interchanges between various public transport components. All experiments tested local effects at a single intersection or corridor.

While the aforementioned studies assumed fixed route choice and mode choice, the two following studies were interested in the long-term effect of bus priority means. Abdelghany et al. (2006) were interested in the long-term effects of bus signal priority strategies on drivers' route choice adjustments and modal shifts. Their approach was to incorporate bus priority within DYNASMART, an assignment-simulation model. As a mesoscopic traffic model, DYNASMART simulates traffic flow by a speed-density relation and represents individual vehicles. Transit vehicles were generated deterministically and dwell times were not calculated explicitly, but taken as a fixed delay on the link capacity. Passengers were generated according to a given time-dependent OD zone demands. As a demand-focus study, each passenger was represented individually with its preferences. Each traveller evaluated four alternatives (private car, one bus line, two bus lines with one transfer or park & ride with one transfer) using a pre-specified deterministic cost function.

Liu et al. (2006) were also interested in the secondary impacts of transit priority. They developed a transport planning tool integrated into DRACULA. The simulation includes supply and demand sub-models that interact with each other according to a learning algorithm, where the demand (in terms of drivers' route choice) for each day is affected by the cost experienced in the preceding day. Therefore, the simulation includes two loops: external (day-to-day) iterations of the demand loop and internal (within-day) iterations of the supply loop. The researchers examined the mid-term affect of a bus lane on the cars flow in terms of route choice, but did not consider plausible changes towards buses at the modal split.

This common approach has benefits when we consider specific aspects of transit operations. It is, of course, less time consuming than developing a complete comprehensive model. However, its limited framework is also a drawback, since it ignores or over simplifies transit operation aspects that are out of its focus. For example, none of the reviewed enhancement studies treats fleet's operation, assuming that transit vehicles are always available to dispatch.

2.4 Developments

Transit simulation models that were developed according to a comprehensive modelling framework stands at the highest end of the integration range. This classification includes transit simulation models that were developed independently or were completely integrated into general traffic simulation models.

Morgan (2002) identified five requirements from an APTS simulator: transit system representation, transit vehicle movement and interaction, transit demand representation, APTS representation and measures of effectiveness. These requirements were completely integrated into MITSIMLab, a microscopic traffic simulation that was designed specially for the design and evaluation of advanced traffic management systems (ATMS) and advanced traveller information system (ATIS) (see Yang and Koutsopoulos, 1996). Morgan used the general traffic management simulator (TMS) component as a platform for an enhanced simulator that is capable to evaluate APTS features. As a microscopic simulation model, the transit vehicle movements and interactions is represented in great details. The dwell time depends on the numbers of boarding and alighting passengers. The representation of trip chaining is limited because of the limitation on network size feasibility. A case-study for alternative transit signal priority implementations in a corridor in Stockholm had been conducted in order to evaluate the overall system time reduction.

One of the main issues in the implementation of transit signal priority is to predict accurately transit travel time between detection and arriving at the intersection. Poor predictions on previous studies caused a poor performance, especially for intersections with near sided transit stops. Lee et al. (2005) developed a microscopic simulation to tackle this problem. Vehicle movements were determined by driver characteristics, lane changing and signal operations, while buses were assigned to constant moderate characteristics: aggressiveness level, speed, acceleration and lane changing profile. In order to represent the stochastic nature of passenger and bus arrivals, the headway and the passenger arrival rate followed a uniform distribution with no fleet considerations. The dwell time was a function of the headway and the passenger arrival rate. The simulation model selected the transit signal priority plan that resulted in the minimal transit travel time in the prediction model. PARAMICS served as a validation tool on a single intersection with one-way transit route.

A comprehensive transit modelling framework was designed by Meignan et. Al (2007). Their multi-agent approach to transit simulation was aimed to improve the representation of travellers'' behaviour. The public transport systems are made up of three components: people behaviours, road traffic dynamics and specific bus-network operations, which include the interactions between the buses, passengers and road traffic. Respectively, the environment includes pedestrian network, road network and bus network. The multi-agent approach considers the roles that each agent plays: Bus plays two roles simultaneously – vehicle and transport service, while traveller plays two roles alternately – pedestrian and bus passenger. While the vehicles' schedules and travellers' routes are pre-determined, their progression is determined by the inter-action between the three components of the system. The researchers developed a hybrid traffic simulation model, where buses and travellers are simulated with a microscopic approach and all vehicles besides buses are simulated with a macroscopic approach.

The literature review shows only few studies that developed complete transit simulation models. Those models allow detailed representation of local transit operation aspects through microscopic modelling. However, there is no transit simulation model that enables system-wide analysis and applications.

2.5 Discussion

Some trends and classifications were described in the above sections in order to present the body of knowledge in the transit simulation field. Many transit-related simulations were conducted through manipulations or specific expansions of simulation models that does not represent transit or by numerical simulations. Those simulations are useful for specific applications or problems, but lack comprehensive and complete transit modelling.

Efforts in modelling public transport and APTS have concentrated on microscopic simulations, as few developed fully-integrated microscopic transit simulations which appropriate to local effects. However, these models are not useful for large-scale applications because of the unnecessary level of details. In contrast, mesoscopic simulation models, which provide modelling of individual vehicles but avoid detailed modelling of their movement, may be useful for system-wide evaluation of transit operations and APTS. As far as we know, there is no mesoscopic transit simulation model except of the simulation model that is the subject of this thesis.

The following table summarizes the reviewed researches that used traffic simulation models to promote the transit simulation field.

Table 2.1: Summary of transit simulation researches

Research	Level of details	Main focus	Level of integration
Khasnabis et al. (1997)	Microscopic (NETSIM)	Transit signal priority strategies	Adjustment
Chang et al. (2003)	Mesoscopic (INTEGRATION)	Transit signal priority strategies	Adjustment
Ding et al. (2001)	Microscopic (CORSIM)	Passenger service mechanisms	Enhancement
Werf (2005)	Microscopic	Bus Rapid Transit	Extension

	(PARAMICS)	Systems	(SmartBRT)
Liu et al. (1999)	Microscopic (DRACULA)	Types of stops and right of ways	Enhancement
Abdelghany et al. (2006)	Mesoscopic (DYNASMART)	Assignment changes due to bus priority strategies	Enhancement
Cortes et al. (2007)	Microscopic (PARAMICS)	Passengers' attributes and bus service operations	Development (MISTRANSIT)
Morgan (2002)	Microscopic (MITSIMLab)	APTS applications	Development
Lee et al. (2005)	Microscopic	Transit signal priority strategies	Development
Liu et al. (2006)	Microscopic (DRACULA)	Assignment changes due to bus lane presents	Enhancement
Meignan et al. (2007)	Hybrid	Multi-agent approach	Development

Chapter 3: BusMezzo development

BusMezzo is the name for the transit simulation components that were developed and integrated into Mezzo, the background platform on which BusMezzo was designed. Mezzo represents the fundamental traffic models as: speed-density relations, shockwaves, turning movement and route choice. These processes are represented through entities as link, OD pair, node, queue, server, vehicle, turning, traffic signal, route and speed-density function, among others. The mesoscopic representation of traffic flow is also used to model the flow of transit vehicles on links, under slight modifications (obviously, transit vehicles does not have a route choice process). The representation of transit operations requires specification of transit-related models in addition to the general traffic representation.

First, section 3.1 describes in brief the main characteristics of Mezzo. The development process of BusMezzo started from the development of a framework for the representation and incorporation of the transit system components (BusMezzo) integrated within Mezzo, as described in the following section. Section 3.3 presents the implementation of the framework in the simulation progression. The characteristics of the transit model components are described in section 3.4, including relevant literature review. Section 3.5 presents the required inputs and available outputs, respectively, and the decisions involved with their design. Finally, section 3.6 summarizes this chapter.

3.1 Mezzo Simulation

The literature review on Chapter 2 revealed that most research efforts in the transit simulation field were on microscopic simulations and on partial adjustments or enhancements. The transit model is developed on the platform of Mezzo, a mesoscopic traffic simulation developed by

Burghout (2004). The transit components are completely integrated into Mezzo.

Mezzo is an event-based simulation model, which incorporates an iterative dynamic traffic assignment procedure. Mezzo models vehicles individually, but does not represent lanes explicitly. Links in Mezzo are divided into two parts (Figure 3.1): a running part, which contains vehicles that are not delayed by the downstream capacity limit; and a queuing part, which extends upstream from the end of the link when capacity is exceeded. Therefore, the queue part at time t holds the vehicles that their earliest exit time is smaller than t. The earliest exit time is calculated as a function of the density in the running part only.

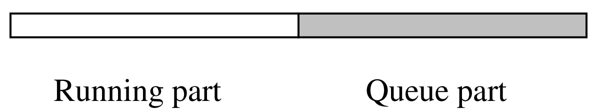

Figure 3.1: The representation of links in Mezzo

Travel times on the running part are determined by the following speed-density function:

$$V(k) = \begin{cases} V_{free} & \text{If } k < k_{\min} \\ V_{\min} + (V_{free} - V_{\min}) \cdot \left[1 - \left(\dfrac{k - k_{\min}}{k_{\max} - k_{\min}} \right)^{a} \right]^{b} & \text{If } k \in [k_{\min}, k_{\max}] \\ V_{\min} & \text{If } k > k_{\max} \end{cases} \qquad (3.1)$$

Where:

V_{free} - Free flow speed (km/h)

k - Density

$k_{\min}$ - Minimum Density where speed is still a function of density

$V_{\min}$ - Minimum Speed

$k_{\max}$ - Maximum Density where speed is still a function of density

a, b - Parameters

This speed-density function promises that the vehicle moves at free flow speed when the density is lower than a given low threshold and has a constant minimal speed if the density is above the high threshold value.

Each connection between links is done through node and is referred as turning movement, including straight movements. The capacity of turning movements is represented by queue servers. Vehicles at the queue part are taken one by one by the queue server and passed to the next link if it is not full. Each turning movement includes a definition of 'queue look back limit' which is the maximum number of vehicles from the front of the queue that the server checks when searching for a vehicle that heads to its direction. Turning servers are modelled stochastically, where independent queue servers for each turning movement regulate delays in the queue according to a truncated normal distribution. The parameters of the stochastic turning movement process are function of the saturation flow rate and the capacity for the specific movement.

Another issue which is a concern for traffic simulation is the problem of representing shockwaves. Shockwaves are discontinuities in density, flow or/and speed. There are six identified prototypes of shockwaves (frontal stationary, backward forming, forward recovery, rear stationary, backward recovery, forward forming), of which Mezzo represents correctly five (excluding 'backward recovery'). The speed of a shockwave is known to be:

$$w_{AB} = \frac{q_A - q_B}{k_A - k_b} \tag{3.2}$$

Where:

w_{AB} - Speed of a shockwave that is a boundary between traffic conditions A and B.

q_i - Flow at traffic condition i

k_i - Density at traffic condition i

The demand is represented by a time-sliced OD matrix. An additional input specifies the percentage for each vehicle type out of the vehicle mix. The interval between vehicle arrivals follows negative exponential distribution. Vehicles are generated at their origin according to the independent related OD pairs. When a vehicle is generated, its destination is pre-determined and its type is set randomly according to the vehicle mix.

Route choice in Mezzo is based on an iterative dynamic traffic assignment procedure, shown in Figure 3.2. The procedure uses the shortest path algorithm to generate new routes, which then results in new travel times according to the Mezzo simulation. This double loop is done iteratively and explicitly with a single exponential smoothing method for the updated historical travel time values. This heuristic algorithm had been shown to converge in practice.

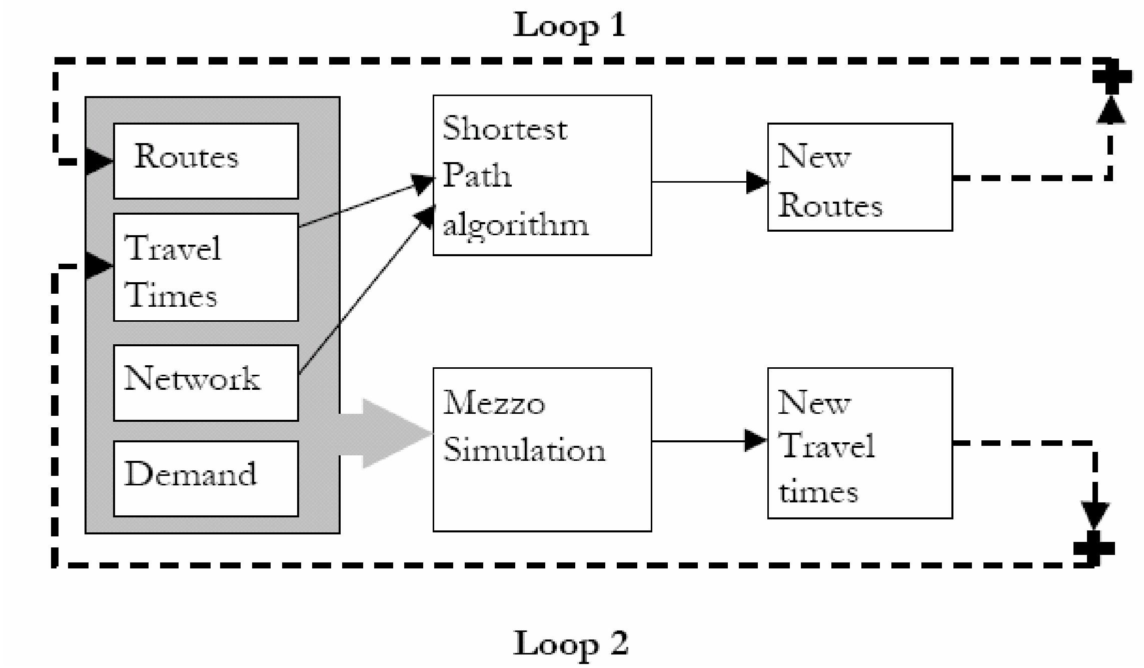

Figure 3.2: Iterative dynamic assignment procedure in Mezzo

Pre-trip route choice follows the MNL (Multi-Nomial Logit) function with a set of known routes and historical link travel times. Mezzo includes also en-route switching mechanism with an updated travel times and routes set, also based on the MNL function. According to the MNL function, the probability that a driver will choose route i is as follows:

$$P_i(t) = \frac{e^{U_i(t)}}{\sum_{j \in S} e^{U_j(t)}} \tag{3.3}$$

$P_i(t)$ - The probability to choose route i at given departure time t

$U_i(t)$ - The utility of route i at given departure time t

S - The set of possible routes between an OD pair

The en-route switching model is based on the comparison between the expected travel time on the alternative shortest route and the expected travel time on the remainder of the current route, both considering delays on the network. The probability for each possible decision results from the MNL model.

While most traffic simulations are time-based, Mezzo is an event-based simulation. Time-based simulations are progressed from one time step to the other, when each equal-size time step calculate all changes and update the state of all network's components. In contrast, event-based simulations are progressed from one event to the other. The simulation determines which changes in the network are treated as events (in Mezzo for example, among others: generating vehicle in the origin or terminating in the destination, turning movements). Events are ordered in an event-list, which in turn call them as they are in top of the stack. While event-based simulations may have computational benefits because of fewer steps, there are computational costs caused by the event-list management.

The input to the Mezzo simulation includes: network description (nodes links, turning movements, servers and speed-density functions), routes, link travel times (historical), demand (OD matrix), vehicle mix and server rates. The simulation calls the master file that refers to all the required input files. The outputs that results from the Mezzo simulation are: measures of effectiveness for each link and each time period (average speed, density, inflow, outflow and queue length), link travel times (simulated) and vehicle trips (path travel time for each OD pair and for each vehicle trips). So the output can be summarized in link, vehicle and OD level.

Mezzo is implemented in a modular manner in C++ code language. The simulation was built under OOP (Object oriented programming) approach in order to enable further enhancements and developments. Each entity in the model (e.g. node, queue, vehicle, OD pair) is represented as an object with its related variables and functions. The objects are related via various reciprocal relations (see Appendix A).

The GUI (Geographical User Interface) uses QT libraries. The GUI (see Figure 3.3 for an example of snapshot) presents the changes in queue length and density during the simulation for each link, displayed by the colour and width of the link. The GUI serves as an observation tool for the simulation duration. Currently, there is no representation dedicated to transport movements.

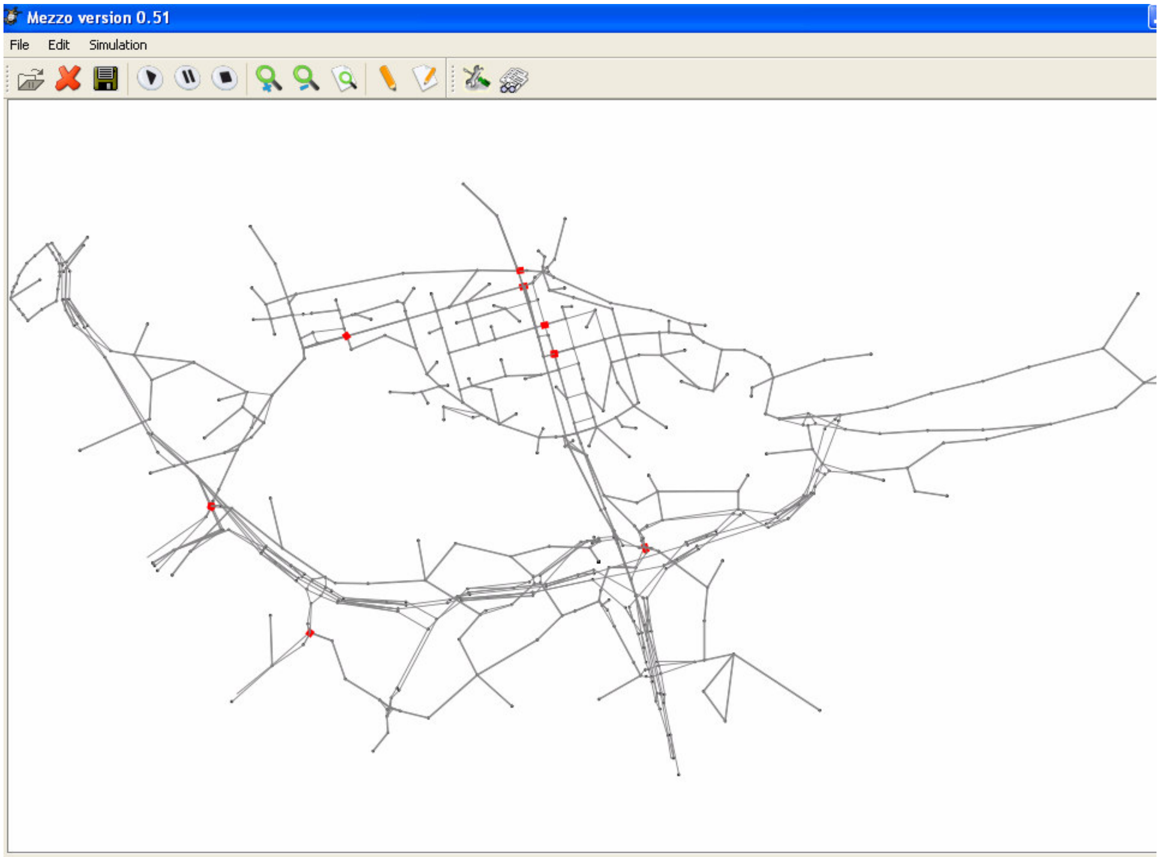

Figure 3.3: Mezzo GUI screen

It should be noted that Mezzo was designed in order to enable hybrid microscopic-mesoscopic traffic simulations in cases where there are different levels of interest along the network. Burghout et al. (2005) illustrated Mezzo capabilities as a hybrid simulation model. The case studies included incident conditions and comparison with field data from a mixed freeway/urban network in Stockholm.

3.2 BusMezzo framework

The development of BusMezzo, the transit-related components in Mezzo simulation, requires a framework for their representation and the way they are integrated into the existing components. A simplified object model of the general Mezzo simulation is presented in Appendix A. Following the object-oriented programming approach, each transit entity is implemented through a unique object (notated by capital letters). The inclusion of transit-related processes requires six additional objects (Figure 3.4):

1. BUSTYPE – The prototype of bus vehicle types. Contains the definitions of bus prototypes and specify their attributes: length, number of seats and passenger capacity. This object is constant during the simulation.
2. BUSVEHICLE – Contains all the variables and function related to a specific bus vehicle. This object inherits the attributes of the general Vehicle object. In addition it specifies the bus type from which it inherits bus attributes. Bus vehicles maintain their driving roster, which allows modelling layover and recovery times in the trip sequence. During the simulation it also updates its occupancy and uses the vehicle capacity to determine crowding levels, and the maximum number of passengers that may board at each stop.
3. BUSLINE – An object for the bus line service definition. Holds information on the line such as its origin and destination terminals, the definition of the line in terms of stops and possible time point stops (where the departure is subject to policy constraints). During the simulation run, it maintains a list of active trips and book the departures for trips on it schedule.
4. BUSTRIP – The object that operates the single bus run. Maintains the schedule for expected arrival time in each stop for

the specific trip. It also calculates the departure time from the origin terminal and books arrival time at bus stops.

5. BUSROUTE – Contains all the variables and function of the bus route in terms of links. This object inherits from the general Route object. The route is defined by an ordered list of links.
6. BUSSTOP – An object for the characteristics and operations involved with bus stop. Holds the link and position on the link that the stop is located at, the length, type (lane or bay) and availability of traveller information. It also holds a list of bus lines that service the stop and the last service time for each. It calculates the number of boarding, alighting and waiting passengers. It also calculates the dwell time and book exit time.

A BUSVEHICLE object inherits from the VEHICLE object, which means that it shares all it variables and functions and has additional unique variables and functions defined (see Appendix B). Similarly, the BUSLINE object inherits from the ACTION object, which defined general procedures for all the objects that invoke the simulation. It should be noted, that Figure 3.4 presents only additional unique characteristics. BUSSTOP refers to a single link according to it location, but each link might has a few bus stops (1:N relationship). The same relationship stands for BUSLINE and BUSTRIP: each trip follows the definition of a single bus line service, while each bus line probably has many trips (or runs) during the simulated period. The figure presents only three objects from the general Mezzo simulation (VEHCILE, ACTION and LINK) that has direct conceptual links to BusMezzo framework. However, BusMezzo and Mezzo are completely integrated and exercise extensive interactions, as Figure 3.4 presents only the extended transit objects to be added to the general object model.

The BUSLINE object has a corresponding BUSROUTE (1:1 relationship) and maintains a list of trips. It initializes BUSTRIP objects according to its trip schedule and may have several simultaneously. A single BUSVEHICLE may serve several BUSTRIPs and is assigned or generated to each trip based on the driving roster and its availability. Thus, trip chaining is explicitly modelled. The BUSTRIP object maintains the route in terms of stops, while the BUSROUTE object holds the route in terms of links. Of course, these objects are not static, as the simulation progress they are generated, initialized, activated, called by other objects, updated, call other objects and terminated. The simulation progress process is described in the following section.

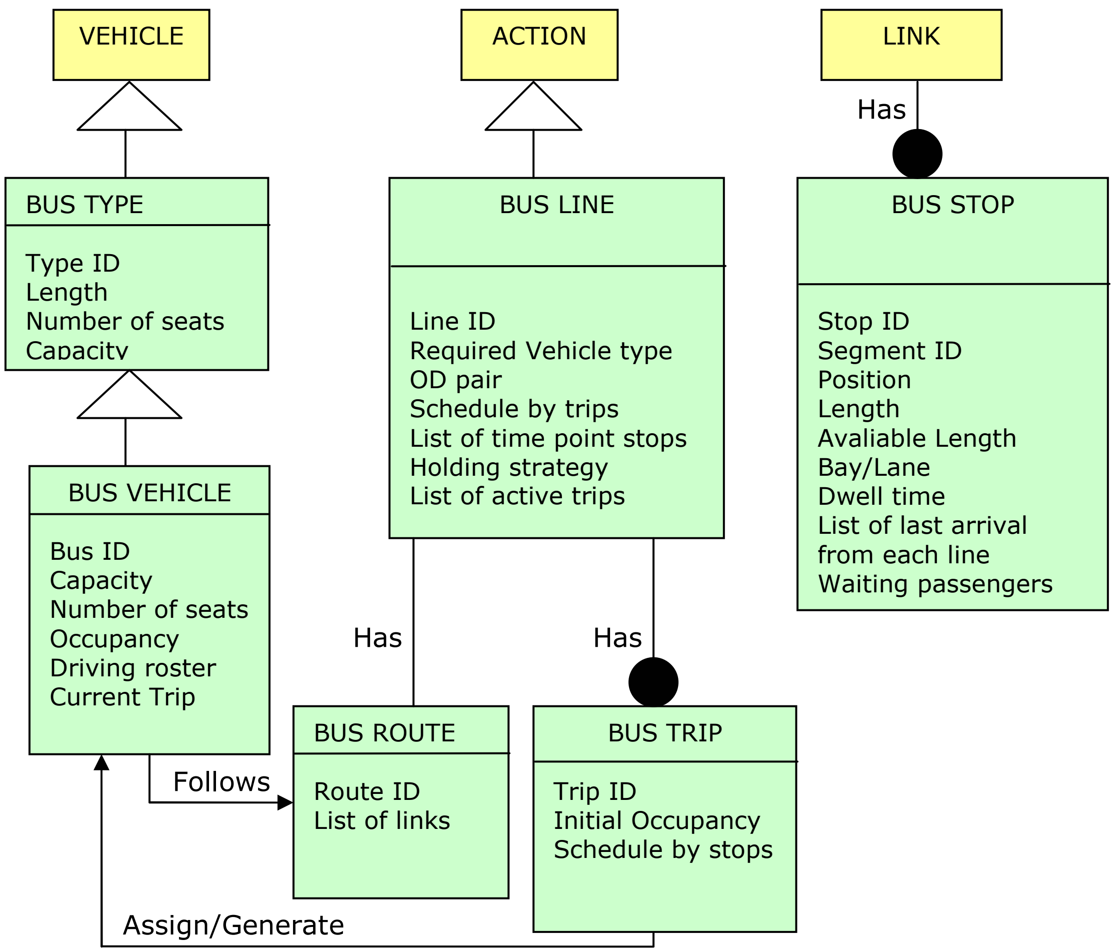

Figure 3.4: Framework for BusMezzo development

3.3 BusMezzo progress

As mentioned above, Mezzo is an event-based simulation. As such, the time clock of BusMezzo simulation progress from one event to the next event according to a list of events, as presented schematically in Figure 3.4. In the beginning of the simulation, all the objects are initialized and some of them register an event (e.g. entering a link). The events are stored in a chronological order and each event indicated the object type that it refers to. The execution of most events triggers the booking of a proceeding event. Therefore, one of the fundamental decisions in the simulation design is which changes in the system would be treated as events.

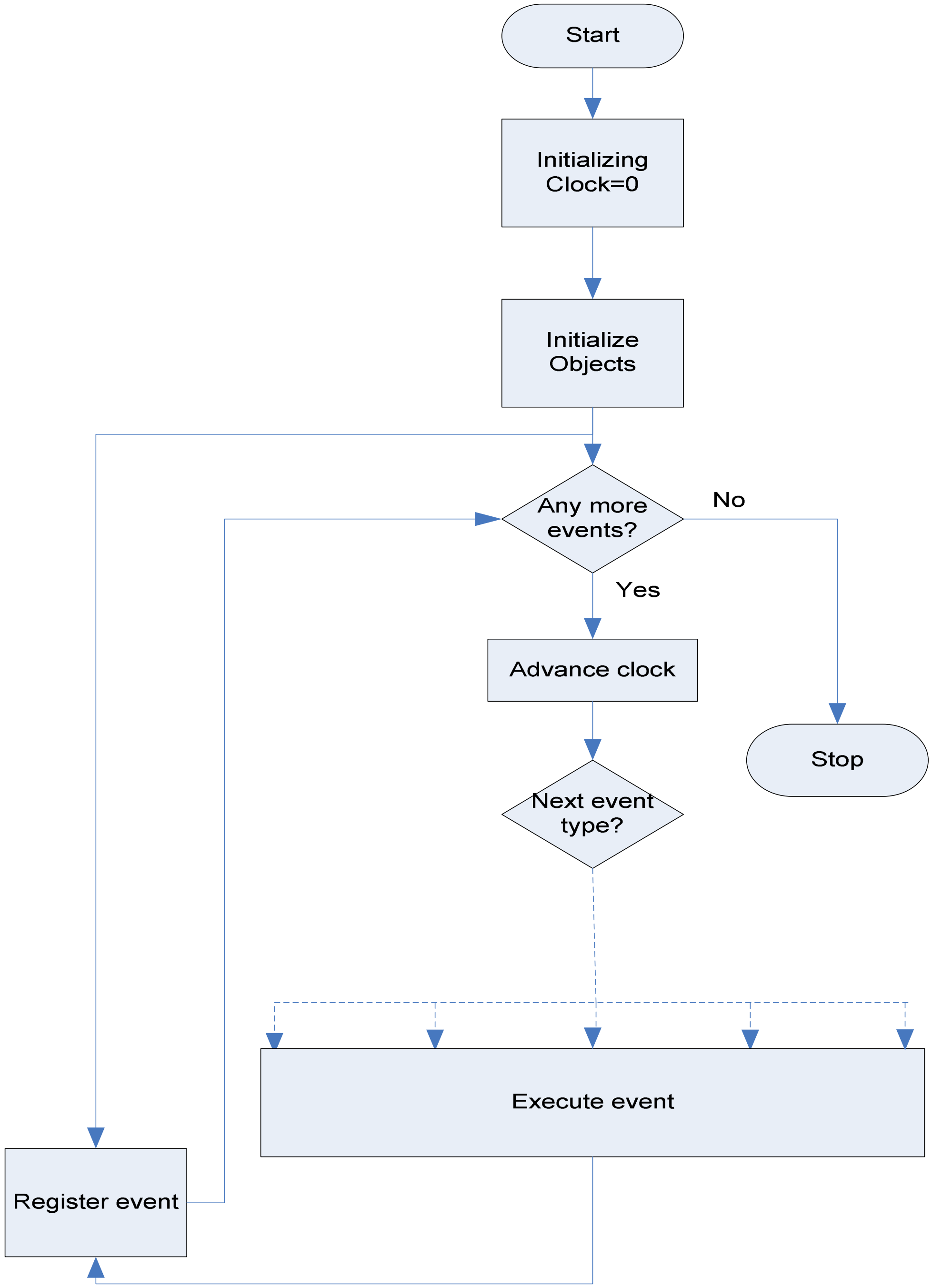

Figure 3.4: Flow Chart of general Mezzo simulation

The flowchart in Figure 3.5 shows the simulation process and the queries that each event triggers. On initialization of the simulation run, a list of the bus lines that are being modelled is read and the corresponding BUSLINE and BUSROUTE objects are created, as well as the BUSTYPE objects. For each bus line scheduled departure times and vehicle assignments are defined.

In the main simulation loop, transit-related events are handled the same way as the other types of events. Initially, an event is registered in the event list for the next departure for each line and a BUSTRIP object is generated. When such event is activated, the simulation checks if the assigned vehicle is available at the scheduled dispatching time and as a result if the dispatching is on-time. The answer to this query may result in several events: if the assigned vehicle is not yet on service (which means that this trip is the first on its driving roster) - then a BUSVEHICLE object has to be generated and inherits the properties of the specified BUSTYPE; if it is the first trip on this bus line, then it has to be activated; once the bus vehicle is available and a BUSVEHICLE object is assigned to the trip, two events are added to the list of events- entering the link and activating the bus trip.

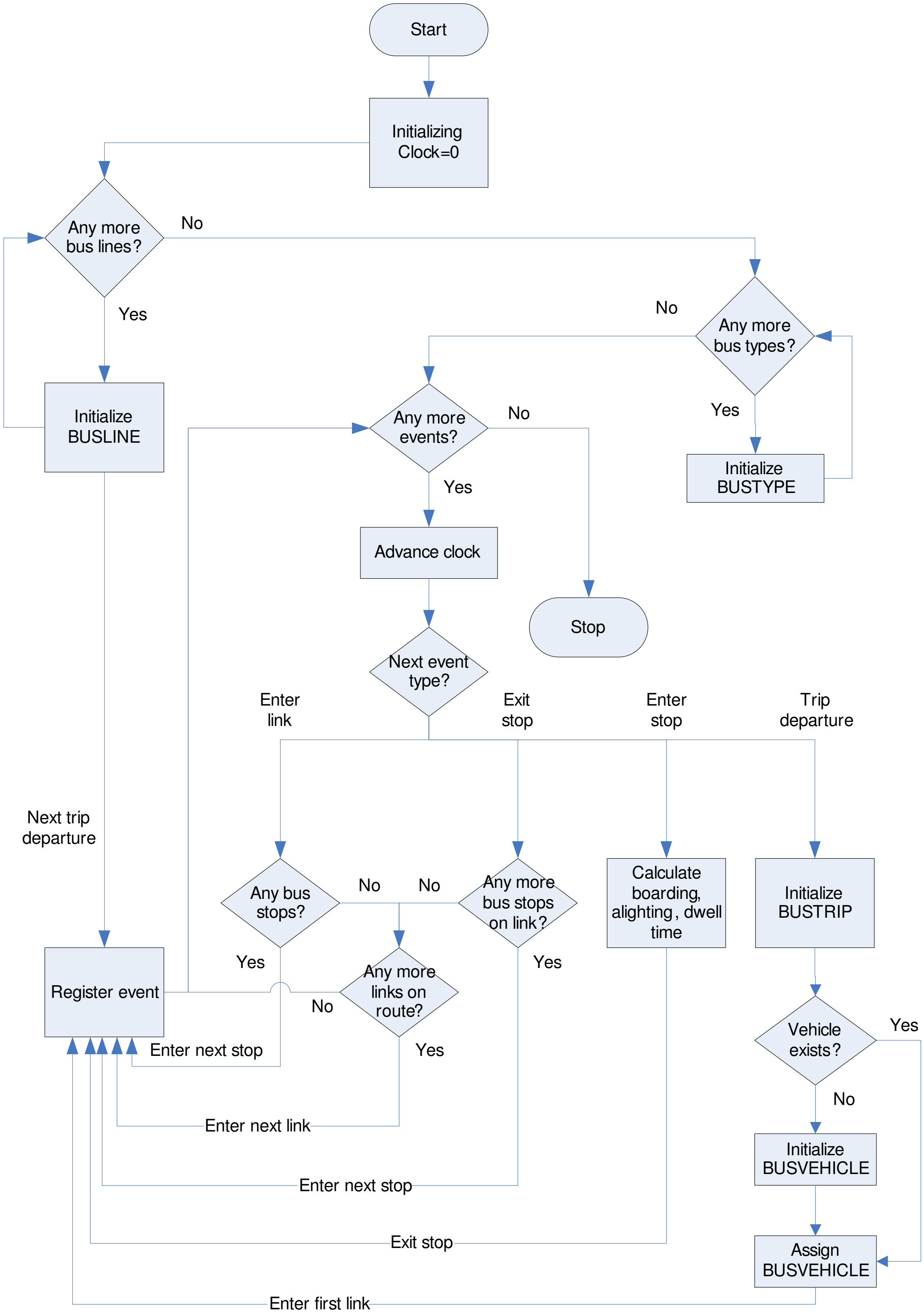

Figure 3.5: Flow Chart of the transit simulation process

When the bus enters a link on its route, it checks whether there is a bus stop it services on this link or not: if there are no stops on this link, then BusMezzo calculates the link exit time and books it. Link travel times are calculated based on traffic conditions as for all vehicles in Mezzo; if there is a stop on this link, then BusMezzo calculates the travel time till the stop and books an event for the stop entry time. The driving time to the stop is a proportion of the link travel time, depending on the location of the stop. Once the bus enters a stop, the simulation calculates the dwell time, checks if any control strategy is implemented and according to the outcomes of those queries, books an event for the stop exit time. When the bus exits the stop, similarly to the event of entering a link, BusMezzo checks if there are any more stops on this link and calculates its driving time to the next stop or to the end of the link based on the current traffic conditions and on the distance to the next stop or the end of the link. An event to enter the next stop or to exit the link is registered. Finally, when the bus arrives at the end of its route, BusMezzo queries if there are additional trips for this bus line and bus vehicle: if the answer is positive, then the next trip is activated and progressed; if this was the last trip for this line or for this vehicle, then the line or vehicle are terminated, respectively.

In summary, the following will be regarded as events by BusMezzo (followed by the name of the object that provokes it):

- Entering or exiting a link (LINK)
- Generating or terminating a vehicle (BUSVEHICLE)
- Starting or ending line service (BUSLINE)
- Starting or ending a trip (BUSTRIP)
- Entering or exiting a stop (BUSSTOP)

Each event triggers some queries and usually involves the booking of other event.

The main simulation loop was designed to enable the implementation of control strategies, which requires an additional phase. As shown in Figure 3.6, the initializing process includes the initialization of control parameters. Each object that is a potential subject for control strategy is indicated by a flag. Every time that that the simulation executes an event, it is followed by two consecutive queries: Checking whether a control strategy is defined for this event (in other words, if there is a flag for the relevant object); and if so, evaluating the control logic (is the criteria satisfied?) to determine the appropriate action. For example, if holding control is in place, then for every bus that enters a stop, the simulation checks two things: first, whether the bus stop is a time point stop and if it is, for how long the bus should be held, if at all.

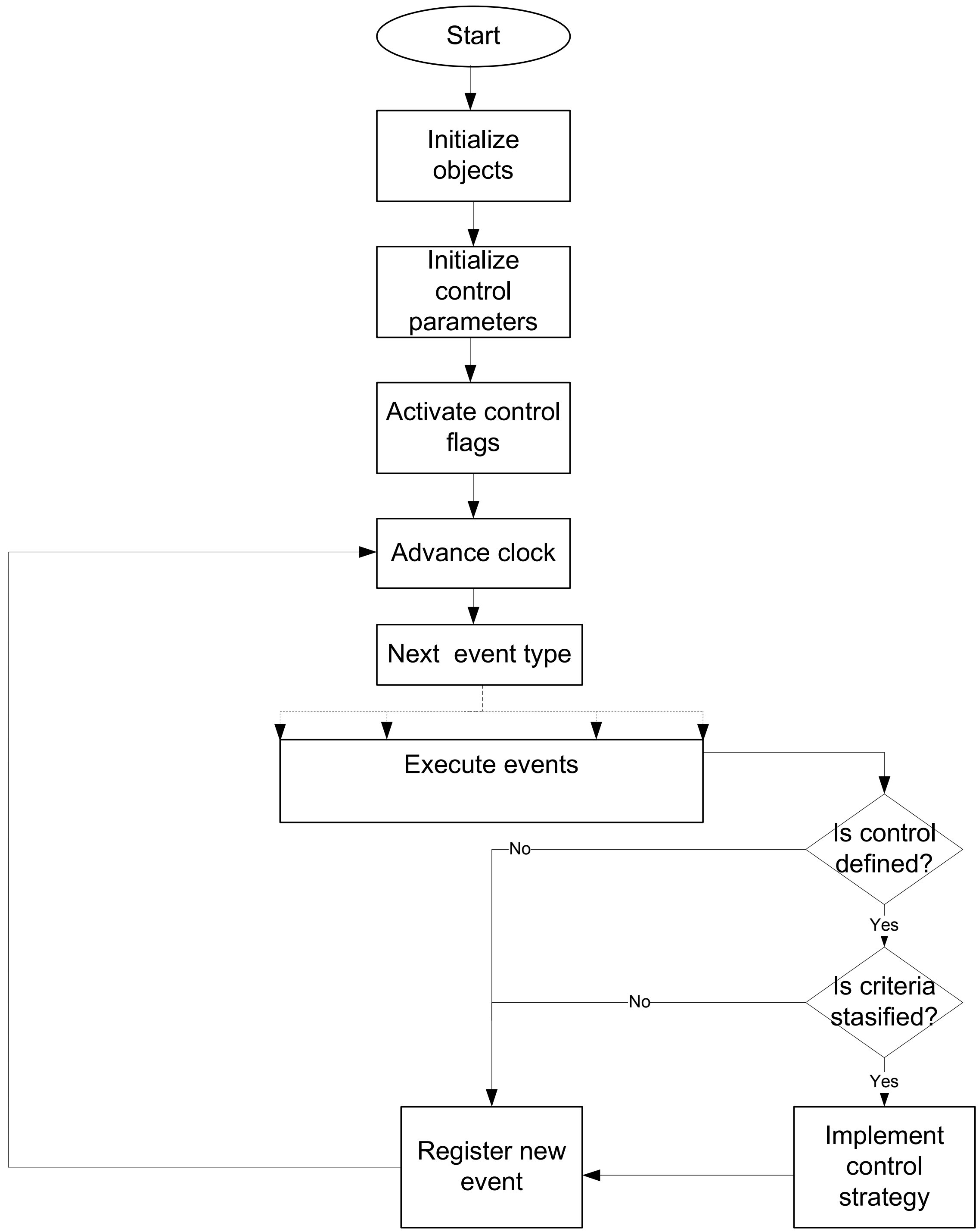

Figure 3.6: Flow Chart of the control process in the simulation

3.4 Transit mechanisms specification

The general structure of BusMezzo and the simulation process were presented in the preceding sections. The following section describes in detail the transit mechanisms represented by BusMezzo. The additional transit simulation components were designed to include detailed representation of the operations of public transport. Elements of the behaviour of these vehicles that are modelled include generation of vehicles based on schedules, chaining of trips, behaviour at stops and a detailed representation of passenger demand at the various stops. Every transit planning or analysis tool has to assume some characteristics (function, distribution) on the transit service mechanisms: boarding and alighting processes, dwell time, running times, departure and delay times, layover and recovery times.

The basic attributes of transit operations as travel time, dwell time, boarding and alighting processes and recovery time are crucial for any model that intends to represent transit operations. These assumptions are in the core of every model because they dictate the demand and supply representation and also the measures of service (e.g. passenger waiting times (Bowman and Turnquist, 1981)). The number of assumptions tends to grow as the transit representation is more local in nature and less comprehensive. For example, a transit simulation that represents a single corridor or several intersections can not represent trip chaining and therefore has to generate bus vehicles in the origin according to an assumed distribution. The common assumptions about the nature of core transit mechanisms are reviewed in the following section. The transit simulation model includes four main components: passenger behaviour, dwell time, travel time and trip chaining. The literature review of relevant findings and assumptions regarding each component is followed by its specification in BusMezzo simulation.

3.4.1 Passengers' behaviour

Every transit simulation must include some representation of the passengers – the demand side of the public transport system. There is a wide range of possible demand representation levels. At the most aggregate level, the passenger behaviour can be set to be constant in all cases. An enhanced model will include a vector of values that varies by one variable (bus stops, bus lines or time periods), or a matrix that varies with several variables. These levels of representation treat passengers in terms of flows and rates, while simulation models that focus on the representation of the demand side include passenger objects so that each passenger is simulated individually. The inclusion of passenger objects enables to represent individual attributes and preferences as modal choice, transfers and stop selection.

The transit simulation model reported in this thesis is transit operations oriented and therefore focuses more on the supply side than on the demand side. Passenger demand, which determines the alighting, boarding and crowding levels, is represented by two components: the demand to get *on* and the demand to get *off* each bus at each stop. BusMezzo represents demand in the most detailed level possible in the aggregate scope - a matrix of time-specific arrival rate and alighting fraction in a given bus stop for a given bus line. This level of representation has to follow some assumptions regarding the boarding and alighting distributions.

Several studies in the 80's changed the convention that passenger arrive randomly in all cases. Bowman and Turnquist (1981) showed that passenger arrival behaviour changes with the service characteristics: passengers arrived randomly for short headway services and followed a right- skewed distribution when headways are long. Moreover, passenger arrival was found to be very sensitive to schedule adherence, much more than it did for service frequency. Abkowitz and Tozzi (1987) showed that empirical data indicated that for headways over ten minutes, passengers waited less then what is expected if they were to follow random arrival process. Seneviratne (1988,1990) also assumed a disaggregate approach that implies that the numbers of boarding and alighting passengers assumed to follow normal distribution at high-density stops and Poisson distribution in low-density stops. In his earlier study, chi-square tests suggested that gamma distribution fits the data better, while the empirical study on his late study reinforced his assumptions. Those results fit the intuition that passengers arrive randomly when the service is frequent and tends to follow the schedule as the headways are longer.

Another study that suggested that passenger behaviour is not simply random was conducted by Guenther and Sinha (1983). The researchers tested the hypothesis that the passengers boarding and alighting rates at each stop follows the Poisson distribution. This hypothesis was rejected by field observations that showed that the Poisson distribution underestimated the extremity cases: stops with a large number of passengers and stops with no boarding and alighting. On the other hand, the negative binomial distribution projected well the number of boarding and alighting passengers. A contradicting later study by Rajbhandari, Chien & Daniel (2003) concluded that the numbers of boarding passengers and alighting passengers matched Poisson distribution. The numbers of boarding and alighting passengers is a vital component by itself, but they are also variables to the dwell time function.

Implementation

Although there are some conflicting results, it can be concluded that passenger arrival tends to follow right skewed distributions. As Table 4.1 indicates, most studies that assumed distributions used the Poisson distribution to describe passenger arrival and Binomial for passenger alighting process. Therefore, it is assumed that passenger arrivals at the stops follows a Poisson process, where the arrival rate describes the average number of occurrences per time unit, in this case- the number of passengers that arrives in a specific bus stop for a specific bus line during the headway from the preceding bus:

$$B_{ijk} \sim Poisson(\lambda_{ijk} \cdot h_{ijk}) \tag{3.4}$$

Where:

B_{ijk} - Number of boarding passengers on line i at stop j on trip k

λ_{ijk} - Arrival rate of passengers at stop j for line i on trip k

h_{ijk} - Headway, time since the preceding bus (on trip $k-1$) to trip k on line i stopped at stop j

The alighting of passengers is modelled as a fraction of the passengers on-board the bus entering the stop. The number of passengers alighting is assumed to follow a Binomial distribution with alighting probabilities, the probability that each passenger will alight, that are stop and line specific. In other words, the alighting fraction describes the average portion of the passengers that will choose to go down from this bus line at this bus stop. Therefore, we can describe the alighting process as a Bernoulli trial for each one of the passengers on board, with each one having the probability of p, which equals to the alighting fraction. Of course, a series of Bernoulli trials follows the binomial distribution, therefore:

$$A_{ijk} \sim B(O_{ijk}, P_{ij}) \tag{3.5}$$

Where:

A_{ijk} - Number of alighting passengers from line i at stop j on trip k

O_{ijk} - Occupancy on line i on arrival at stop j on trip k

P_{ij} - The probability that a passenger on line i will get off the bus at stop j

Passenger behaviour is stochastic in nature – not in any given trip the same number of passengers will board or alight – the simulator was designed to generate random numbers according to various distributions. The most straightforward way to generate random numbers from a Poisson distribution is to take advantage of the relations with the negative exponential distribution. The negative exponential distribution with the same parameter (arrival rate) describes the time gaps between sequential passenger's arrivals. Therefore, we can sum up time gaps (created from a negative exponential generator based on the inverse transform method) until we reach the required time period. The disadvantage of this method is that the number of calls for the random generator is with linear relation with the number of passengers. Since this number could be easily in the dozens, it seems an expensive computational effort. Instead, the simulation generates Poisson random variables according to the inverse transformation method, with the arrival rate pre-calculated to match the headway. Similarly, the binomial random generator is also based on the inverse transformation method (and not on multi-calls to a Bernoulli random generator).

3.4.2 Dwell time

Transit trip time is made up of two components: travel time and time spent at stops, also known as dwell time. Dwell time includes the time till the doors are open, boarding and alighting time, the time till the doors are closed and the time to get off the stop and re-enter the traffic. Based on a field surveys that were conducted in several U.S. cities, Levinson (1983) concluded that dwell times contribute 9 to 26 percents of the total travel time, while 12 to 26 percents is spent in traffic delays. The importance of dwell time to transit operation led to intensive research about its factors. Many dwell time studies used regression models to estimate the independent variables. The following presents suggested dwell time functions and their assumptions regarding boarding and alighting processes.

The first efforts concentrated on identifying the independent variables of the dwell time function. Kraft and Bergen (1974) used the method of least squares to check the effects of various variables and found that the dwell time per passenger changed with the time of day, types of service, vehicle and passenger and method of fare collection. In a continuous study, Kraft and Deutschman (1977) hypothesized, based on the queuing theory, that the passenger service time distribution follows the Erlang function. A validation test did not reject the hypothesis and concluded that the parameters of the distribution are the number of doors on the vehicle, the average service time and the minimum service time. Deuker et al. (2004) preformed regression analysis on a very large sample of observations, collected via AVL and APC (Automatic Passenger Counters) systems. The numbers of boarding and alighting passengers were the most significant factors, in addition to early (or late) arrival, time of day and type of route.

Other studies tried to estimate the dwell time function form. Levinson (1983) estimated the dwell time by using the following formula:

$$DT_{ijk} = \alpha_1 + \alpha_2 \cdot (A_{ijk} + B_{ijk}) \tag{3.6}$$

Where:

DT_{ijk} - Dwell time for line i at stop j on trip k

α_1, α_2 - Parameters

This formula indicates that each passenger, whether boarding or alighting, requires the same service time.

In contradiction, Guenther and Sinha (1983) found that total dwell time per stop follows the law of diminishing returns, meaning that as the number of passengers at a stop increase the total dwell time increases but the time per passenger decreases. A regression analysis found this relation to be:

$$DT_{ijk} = (\alpha_1 - \alpha_2 \cdot [\ln(A_{ijk} + B_{ijk})]) \cdot (A_{ijk} + B_{ijk}) \tag{3.7}$$

However, the variation of dwell time depends significantly on other factors as well, as the relatively low value of R^2 suggests (R^2=0.36).

The preceding formulas do not distinguish between boarding and alighting processes. Lin and Wilson (1992) developed dwell time functions for light rail trains based on the data from MBTA (Massachusetts Bay Transportation Authority) green line in Boston. Each light rail vehicle has a number of doors so the dwell time of a single vehicle is determined by the door with the longest dwell time:

$$DT_{ijk} = \max_{w \in W}(DT_{ijk}^{w}) \tag{3.8}$$

Where:

DT_{ijk}^{w} - Dwell time for door w

W - Number of doors per light rail vehicle

Similarly, if the LRT is made up of several cars then the total dwell time is the maximum dwell time of individual cars. The researchers added the effect of crowdedness caused by the interaction between boarding passengers, alighting passengers and passengers on board to the direct effects of boarding and alighting passengers. Their suggested dwell time (per door) function is of the form:

$$DT_{ijk} = \alpha_1 + \alpha_2 A_{ijk} + \alpha_3 B_{ijk} + \alpha_4 (A_{ijk} \cdot C_{ijk}^A + B_{ijk} \cdot C_{ijk}^B) \tag{3.9}$$

Where:

C_{ijk}^A - Number of alighting standees on the bus

C_{ijk}^B - Number of boarding standees on the bus

This model is based on the assumptions that boarding and alighting rates decrease as the crowdedness factor increases and that the crowdedness factor effects both rates identically. Results of linear regression models showed that models that did not include terms representing passenger crowding had poor goodness of fit measures, while the suggested model had R^2=0.62. In addition, the effect of crowding seems likely to be nonlinear so that the marginal delay increases with the number of standees. Following this study, Poung (2000) performed least squares regression for the dwell time on the MBTA red line. The analysis resulted in a linear effects for boarding and alighting passengers and nonlinear crowding effect (R^2=0.89):

$$DT_{ijk} = \alpha_1 + \alpha_2 A_{ijk} + \alpha_3 B_{ijk} + \alpha_4 (B_{ijk} \cdot C_{ijk}^B) \tag{3.10}$$

Interestingly, the nonlinear contribution of the passenger load involves only the boarding process, so the marginal boarding time increases as the number of standees does. It was also found that the crowding factor explains 90% of the dwell time variation.

An additional study by Rajbhandari, Chien & Daniel (2003) examined four regression models based on the numbers of boarding and alighting passengers and the number of standees. The estimated parameters indicated that a boarding passenger contributes to the dwell time more than an alighting passenger. In addition, the model that included the number of standees (similar to equation 3.9) was found inferior to the simple nonlinear model:

$$DT_{ijk} = \alpha_1 \cdot (A_{ijk} + B_{ijk})^{\alpha_2} \qquad (3.11)$$

The dwell time per stop and the service time per passenger were found to follow log-normal distribution. In addition, time of day and service type had no significant impact on the dwell time.

As a comprehensive transit operations manual, the Transit Capacity and Quality of Service Manual (TCRP, 2003) presents a method to calculate the dwell time. Its method is based on the dwell time at the highest volume door and the proportions of boarding and alighting processes through the bus doors. The dwell time per boarding passenger depends on the fare payment procedure and present of standees, while the time per alighting passenger is different for the front door and the rear door. According to the manual, dwell times follow the normal distribution and the coefficient of variation of dwell times is in the range of 0.6 to 0.8. When the bus stop is out of traffic (in a bay) there is also re-entry delay - the time to find a suitable gap and re-enter the traffic. This additional delay is estimated as a function of the mixed traffic volume in the adjacent lane. Similarly, Ceder (2007) concluded from previous works that the accepted dwell time function follows a linear model with a differentiation between single-door vehicles and double-door vehicles. The dwell time function for single-door vehicles:

$$DT_{ijk} = \begin{cases} \alpha_1 + \alpha_2 A_{ijk} + \alpha_3 B_{ijk} & \text{if } A_{ijk} > 0 \text{ or } B_{ijk} > 0 \\ 0 & \text{if } A_{ijk} = B_{ijk} = 0 \end{cases} \qquad (3.12)$$

While the function for double-door vehicles assumes, unlike the TCQSM (TCRP, 2003), that passengers board only from the front door and alight only from the rear door:

$$DT_{ijk} = \begin{cases} \alpha_1 + \max(\alpha_2 A_{ijk}, \alpha_3 B_{ijk}) \\ 0 \end{cases} \quad (3.13)$$

Ceder also summarized the commonly used values of the parameters: dead time per stop (constant), boarding and alighting times per passenger as function of fare payment and baggage.

Implementation

BusMezzo is designed to allow the flexibility to specify a wide range of dwell time functions. In the current implementation, the dwell time function was based on the Transit Capacity and Quality of Service Manual (TCRP, 2003), which used the number of passengers boarding, passengers alighting and the crowding on the bus as explanatory variables. The dwell time is determined by the highest volume door and the proportions of boarding and alighting processes through the bus doors. In addition, the function differentiated between stops that are placed in-lane and those that use a bus bay. An in-lane stop causes delays to the general traffic, but the dwell time is longer with bus bays due to the time needed for the bus to find a suitable gap in traffic in order to re-enter the lane when exiting the stop. Furthermore, the function assumed that when there is no space left at the stop, buses alight and board passengers out of the stop and dwell times increase. The resulting dwell time function is given by:

$$DT_{ijk} = \beta_1 + \max(PT_{ijk}^{front}, PT_{ijk}^{rear}) + \beta_2 \cdot \delta_j^{bay} + \beta_3 \cdot \delta_{ijk}^{full} \quad (3.14)$$

Where:

PT_{ijk}^{x} - Total passenger service time on door x

$$\delta_j^{bay} = \begin{cases} 1 & \text{Bus stop is on a bay} \\ 0 & \text{Otherwise} \end{cases}$$

$$\delta_{ijk}^{full} = \begin{cases} 1 & \text{Bus stop is fully occupied} \\ 0 & \text{Otherwise} \end{cases}$$

$\beta_1, \beta_2, \beta_3$ - Dwell time function parameters

The main component, the total passenger service time, is demand-dependent and is determined as follows:

$$PT_{ijk}^{front} = \alpha_1 \cdot p_{front} \cdot A_{ijk} + \alpha_2 \cdot B_{ijk} + \alpha_3 \cdot \delta_{ijk}^{crowded} \cdot B_{ijk} \tag{3.15}$$

$$PT_{ijk}^{rear} = \alpha_4 \cdot (1 - p_{front}) \cdot A_{ijk} \tag{3.16}$$

Where:

p_{front} - The fraction that alight from the front door

$$\delta_{ijk}^{crowded} = \begin{cases} 1 & \text{Bus vehicle is crowded (50 passengers)} \\ 0 & \text{Otherwise} \end{cases}$$

$\alpha_1, \alpha_2, \alpha_3$ - Passenger service time parameters

In summary, the current implementation calculates the dwell time as function of:

- Number of boarding passengers
- Number of alighting passengers
- Distribution of alighting passengers between vehicle's doors
- Crowdedness factor
- Type of stop
- Stopping space availability

3.4.3 Travel time

The majority of transit trip time is the driving time between stops. Bus travel times depend on various variables: distance, congestion, traffic signals, crossing intersections, lane changing and driver characteristics. But in addition to the variables that affect every vehicle, the urban bus is subject to special driving regime due to its need to decelerate, stop and accelerate every few hundreds of meters. As the transit service has a more segregate right of way (e.g. transit lane, transit way, underground), the travel time variability decreases and the service reliability increases. Taylor (1982) analyzed competing bus and metro travel time data. A Chi-square and Kolmogorov-Smirnov tests suggested that bus travel time followed normal distribution, while metro run time was represented by a log-normal distribution.

A number of studies examined the relations between running times, headway variation, arrival times, delays and passenger waiting times. Abkowitz and Tozzi (1987) identified in their review three chronological research methodologies in this field: analytical approaches, empirical analysis and the rise of simulation models (that started to develop at the time). Many of the reviewed works called for simulation models that allow expanding the problem complexity and improving the representation of various bus characteristics. According to the study, analytical approaches failed to model headway variation, but regression analysis on empirical data suggested that headway variation tends to propagate at stops downstream the route with a non-linear relation between headway variation and running time variation. Regression models estimated the mean running time mainly as function of distance, boarding and alighting passengers and number of signalized intersection, while the variation of running time was estimated by a linear regression model as a function of the mean running time.

Strathman et al. (1999) studied the variation of service reliability with data from the bus system in Portland, Oregon. An analysis of the data indicated that headway variation is positively correlated with running times, while both of them are negatively correlated with on-time performance. In addition, the distributions of arrivals and delays had a log-normal form, while the headway distribution had a symmetric distribution that represents the bus-bunching phenomenon. Those results are in agreement with Dessouky et al. (1999) finding that most past studies, both theoretical and empirical, used positive skewed distributions as lognormal, gamma or Gumbel to describe arrival time and travel time (which means that buses are expected to be behind schedule more than ahead of it). They also found through an empirical analysis that there is a negative correlation for long-headway bus lines between lateness at the start of the segment and delay in the end of the segment. This tendency to catch up with schedule is counter to the positive correlation that exists for short-headway bus lines because of additional boarding passengers, which contributes to the bunching phenomenon.

Implementation

As is evident in Table 3.1, all the reviewed researchers found that bus arrivals and travel times tends to follow right skewed distributions, usually Lognormal. However, when it comes to studies that only used assumptions regarding travel time distribution, Normal, Gamma and Lognormal were equally used. BusMezzo allows flexibility in determining travel time variability. In case that detailed background traffic data (OD matrix) is not available or not important for the evaluated application, it is possible to generate travel times according to a pre-determined distribution. This method saves data collection and computational efforts and time, when appropriate. In addition, it is possible to determine different variability parameters for different levels of segregated right of ways (e.g. lower variability for bus ways).

3.4.4 Trip chaining

In addition to the published service schedule, there is a schedule at the bus vehicle level, which is used by the bus company and the drivers for operation and logistics. Each vehicle and driver has a daily schedule with a list of the trips to be done, also known as driving roster. Layover time is aimed to serve as a buffer between successive parts of the ride, in order to avoid the propagation of delay along the route. There are three methods to allocate the layover time: spread along the line, concentrated in the end of the trip (at the terminal) or a combination (TCRP, 2000). Recovery time allows the service to recover from a delay in the previous trip in order to departure on time from the terminal on the next trip. Alternatively, it allows the driver to rest between successive trips. The representation of trip chaining enables the simulation to capture the dependence between successive trips, an important operational issue.

There are several methods to determine the size of the layover and recovery time. The objective of all the methods is to balance between two contradicting goals: high dispatching reliability which requires long recovery and layover time and high efficiency which requires the smallest possible margins between chained trips. Strathman et al. (2002) mentioned three common criterions for the duration of the recovery time: (1) Levinson's optimal recovery time – the difference between the mean or the median and the 95th percentile running time; (2) according to the operator contract; (3) the rule of thumb – 18% of the median running time. The authors preformed regression analysis which suggested that transit operator accounts for 17% of the variation in running times, for example - by unexplained late dispatching.

Implementation

The Vehicle class in MEZZO generates and eliminates vehicles according to an OD demand matrix. Buses, however, should be eliminated only when their chain of trips is completed (deadheads should be inserted in the input file as any other trip with an OD pair and no intermediate stops.). If all trips were to follow the schedule perfectly – there was no benefit in simulating trip chains. Since traffic is stochastic sometimes buses arrives late at their destination and start late their chained trip. Moreover, there is always some necessary recovery time. Dispatching time is calculated as the later between the scheduled dispatching time and the time the bus vehicle is available to depart:

$$ET_{vk} = \max\left(ST_{vk}, AT_{v,k-1} + RT_{\min}\right) + \varepsilon_{vk} \tag{3.17}$$

Where:

ET_{vk} - Actual dispatching time for trip k by vehicle v

ST_{vk} - Scheduled dispatching time for trip k by vehicle v

$AT_{v,k-1}$ - Arrival time at the departure stop from previous trip

$RT_{\min}$ - Minimal recovery time between trips

ε_{vk} - An error terms that follows lognormal distribution

3.4.5 Summary

This section reviewed the characteristics of the core transit mechanisms in BusMezzo: passenger demand, the couple of service time components: dwell time and travel time and trip chaining. Although there are many conflicting results regarding characteristics of the various bus mechanisms, a few conclusions can be drawn. The dwell time function is determined by the door with the longest service time and the service time is a function of passenger demand: the number of boarding and alighting passengers. Moreover, passenger and bus arrival tends to follow right skewed distributions. Table 3.1 summarizes the distributions of bus mechanisms that were assumed or found in the reviewed researches. Note that most studies that assumed distributions used the Poisson distribution to describe passenger arrival, Binomial alighting and Gamma for passenger service time. The trend is less clear on the bus travel related processes, where Normal, Gamma and Lognormal were equally used.

Table 3.1: Summary of assumed or found distributions regarding bus mechanisms

*	Research	Passenger-related processes	Bus travel- related processes
A	Liu et al. (1999)	boarding ~ Normal	
A	Cortes et al. (2007)	boarding ~ Uniform	arrival ~ Uniform
A	Morgan (2002)	boarding ~ Poisson, alighting ~ Binomial	
A	Lee et al. (2005)	boarding ~ Uniform	headway ~ Uniform
F	Kraft and Deutschman (1977)	passenger service time ~ Erlang	
F	Bowman and Turnquist (1981)	boarding for short-headways ~ Uniform/ for long-headways ~ right skewed distribution	

F	Guenther and Sinha (1983)	boarding, alighting ~ Binomial	
F	Seneviratne (1988,1990)	boarding, alighting in high-demand stops ~ Normal/ in low-demand stops ~ Poisson	
F	Rajbhandari, Chien & Daniel (2003)	boarding, alighting ~ Poisson; Dwell time, passenger service time ~ Lognormal;	
F	TCQSM (2003)	dwell time ~ Normal	
F	Taylor (1982)		bus travel time ~ Normal; metro travel time ~ Lognormal
F	Dessouky et al. (1999)		travel time, arrival time ~ Lognormal/Gamma
F	Strathman et al. (1999)		arrival time, delay ~ Lognormal
A	Turnquist and Blume (1980)	boarding ~ Random	
A	Vandebona and Richardson (1986)		dispatching ~ truncated normal
A	Senevirante (1990)	boarding, alighting in high-demand stops ~ Normal/ in low-demand stops ~ Poisson; passenger service time ~ Gamma	travel time ~ Normal,

A	Wirasinghe and Liu (1995)		travel time, departure time ~ Gamma
A	Liu & Wirasinghe (2001)	boarding ~ compound Poisson; alighting ~ Binomial; Passenger service time ~ Gamma	travel time, dispatching ~ Gamma,
A	Fu and Yang (2002)	boarding ~ Poisson	travel time ~ Normal
A	Dessouky et al. (2003)	boarding ~ Poisson; passenger service time ~ Gamma	Travel time ~ Lognormal

* 'A' stands for assumed distribution and 'F' stands for found distribution

The approach in BusMezzo model specification, was to allow maximum flexibility and modularity, while using the most accepted and reasoned characteristics found in the literature. Passenger arrival follows the Poisson process, while the number of alighting passengers is subject to Binomial process. The dwell time function is based on the TCRP (2003) guidelines and depends on the number of boarding and alighting passengers in each door, crowdedness factor, type of stop and available space at stop. Travel time depends on the traffic conditions, but it can also vary according to a Lognormal distribution. Trip chaining includes the definition of layover and recovery times. All these elements where integrated into BusMezzo as described above.

3.5 Input and Output

BusMezzo simulation, like all models, requires a set of input data and generates output data. Since BusMezzo is a stochastic simulation model, different runs with the same input data will generate different output results. Section 3.1 mentioned the inputs required by the general Mezzo program. In addition, BusMezzo requires transit-related data in order to simulate the public transport system. This input can be classified into four categories:

1. Routes - Each bus line has a unique route in terms of links sequence and in terms of stops sequence. The route in terms of links is stored in BUSROUTE object, while the route in terms of stops is stored in BUSLINE object.
2. Time tables - There are two complementary time tables involved in bus operations: service schedule and driving roster. Firstly, the service schedule is published to the passengers and presents the expected arrival time for each bus trip in each bus stop. Each BUSTRIP object contains the scheduled times for the stops along its route. Secondly, the driving roster is used by the operator to allocate vehicles and drivers to bus trips. The BUSVEHICLE objects store it sequence of trips and scheduled departure times.
3. Demand – The demand matrix is line and stops specific. Each BUSSTOP object holds for each passing line its passenger arrival rate (hourly flow) and alighting fraction (percentage).
4. Characteristics – Bus vehicles and bus stops have special characteristics that influence transit operations. Most important, the location of bus stops is defined by the link on which it is placed and the absolute distance from the origin node. In addition, the bus stop length is specified as well as the stop type (in-lane or bay). All these details are stored in the BUSSTOP object. The input files should also define the vehicle type prototypes (e.g. minibus,

suburban, articulated). Each BUSTYPE object definition includes the vehicle length, number of seats and maximum capacity. Then, the input specifies the vehicle type for each BUSVEHICLE.

The input text files were designed to have the most direct and clear format. The main design principle was to balance between maximum modularity and flexibility, on one hand, and minimal possible repetitions and encumbrance, on the other hand. Table 3.2 summarized the input according to BusMezzo objects. Further details on the input files format are available on Appendix D.

Table 3.2: Main input required for BusMEZZO objects

Object	Required input
BUSLINE	▪ List of stops
BUSTRIP	▪ Scheduled arrival time per stop
BUSSTOP	▪ Passenger arrival rate per line ▪ Alighting fraction per line ▪ Location: link and position ▪ Stop length ▪ Stop type
BUSROUTE	▪ List of links
BUSVEHICLE	▪ List of trips
BUSTYPE	▪ Vehicle length ▪ Number of seats ▪ Maximum capacity

BusMezzo generates detailed output on transit operation, in addition to the general traffic output generated by Mezzo simulation. The simulation is designed to generate output record every time a bus exits a bus stop. Every bus visit record includes the following basic data: line ID, trip ID, vehicle ID, stop ID, arrival time, scheduled time, delay, dwell time, exit time, headway at arrival, headway at departure, boarding passengers, alighting passengers, occupancy, passengers left behind. Additional possible outputs includes absolute deviation from schedule and binary indicators (according to the defined criterion) as: on-time performance, was the control activated?, is it over-crowded (binary), was it bunched? The text output file can be copied directly to any data analysis software as Microsoft Excel or MATLAB.

Because of the stochastic nature of BusMezzo, it is necessary to find the average of several simulation repetitions, in order to evaluate each executed scenario. Crude outputs are at stop level statistics. Aggregations at the level of the trip, the vehicle or the line, such as schedule adherence, headway and passenger wait time distributions, load profiles, time-space diagram and other level of service measures are also computed. These transit operational measures are aggregated also in system level to enable the evaluation and comparison of scenarios and strategies.

3.6 Summary

The development of BusMezzo, a mesoscopic transit simulation model, had been described. The transit modelling framework includes six transit objects with unique characteristics and functionality. These objects are completely integrated into Mezzo by inheritance and numerous interactions and links. BusMezzo simulation initializes each object according to the input and progresses via calls to a list of booked events. Each event triggers the relevant queries, execute some transit operations (e.g. board and alight passengers or dispatch bus vehicle), books consecutive event and generate output record if required. Control decision making is implemented according to pre-determined criteria that is checked every time that the relevant event is executed.

Every transit planning or analysis tool has to assume some characteristics on the fundamental transit operations mechanisms: passengers' behaviour, dwell time, travel time and trip chaining. Following literature review about the characteristics of each model component, the common attributes were implemented in BusMezzo in modular design. The comprehensive modelling approach intends to develop a simulation tool that enables the evaluation of various transit operations, including APTS, for system-wide applications. BusMezzo capabilities are examined in the following chapter.

Chapter 4: Demonstration

In this chapter the capabilities of BusMezzo simulation will be demonstrated via its application to a real-world bus line. The demonstration is aimed to test the various model components that were described in the preceding chapter and to present the scope of outputs in terms of level of aggregation. First, the examined route and scenarios are described, followed by the simulated distribution of different bus mechanisms. Afterward, the dynamics of service measures along the route are demonstrated, followed by the comparison of system-level measures for various scenarios and a summary.

4.1 Route description

In order to demonstrate its capabilities, the transit simulator is applied to a case study to evaluate the operations of line 51 in the Tel Aviv metropolitan area in Israel. The line route and demand profiles for the inbound and outbound directions are shown in Figure 4.1 and Figure 4.2, respectively. Note that the left side scale refers to the number of boarding and alighting passengers, while the right side scale refers to the occupancy. This high demand urban line connects a dense satellite residential city to the CBD. Its 14 kilometres long route follows a heavily congested urban arterial. As shown schematically in the figures, buses on this route travel about 65% of the distance on a dedicated bus lane, 12% on a completely separate bus way and the remaining 23%, mostly at both ends of the route, on standard streets shared with other traffic. The line includes 30 stops in the inbound direction and 33 in the outbound direction. The peak period frequency is about 8 minutes and the average running time is 49 minutes inbound and 41 minutes outbound.

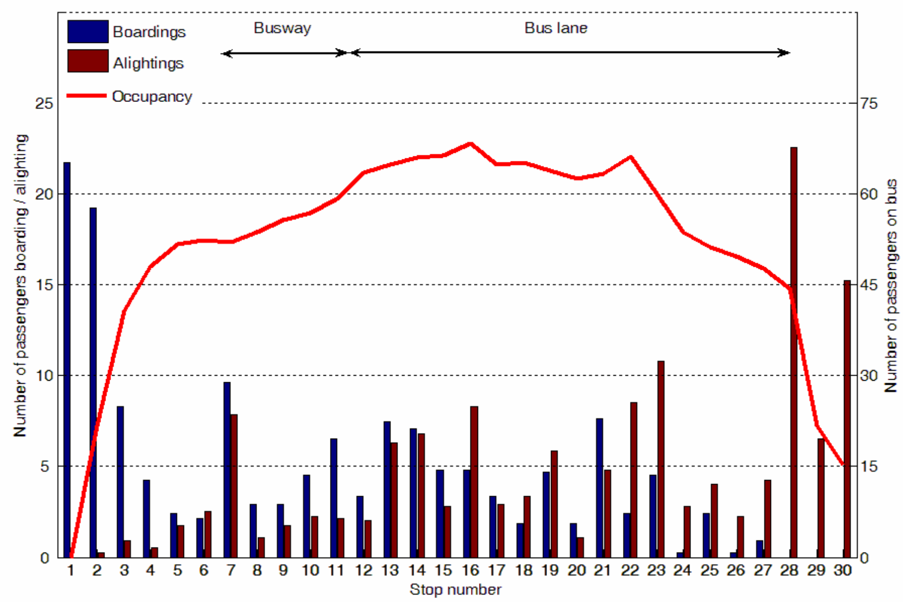

Figure 4.1: Schematic route and demand profile for inbound line 51

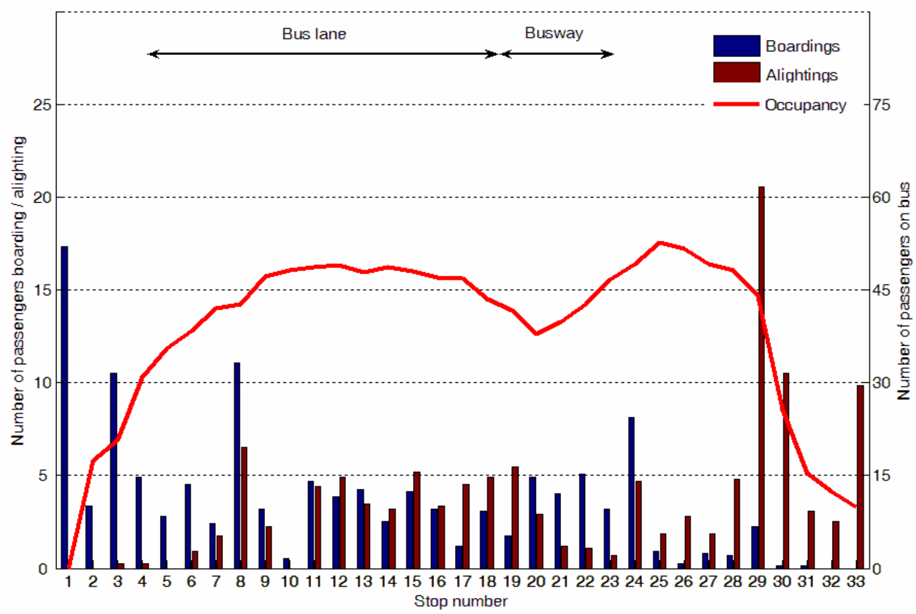

Figure 4.2: Schematic route and demand profile for outbound line 51

The evaluation experiment included study of the impact of two factors on the line performance: the passenger demand and travel time variability. Table 4.1 summarizes the values of these factors. Values are based on those found in literature (Taylor 1982, Fu and Yang 2002, Dessouky et al. 2003) for different segregation levels. Nine different scenarios, one for each possible combination of factor values were run. For each scenario 10 simulation runs were conducted for a four hour period between 6AM and 10AM. The peak-hour demand was generalised for the entire simulation duration. The execution time for a single run was about 45 seconds, and so the 90 runs took about 67 minutes to complete.

Table 4.1: Factors and their levels in the demonstration

Factor	Levels
Passenger demand	80%, 100%, 120% of observed demand profile
Travel time variability	80%, 100%, 120% of mean travel time

Running times between stops were assumed to follow lognormal distributions, with means that equal the scheduled times:

$$T_l = T_{l,\min} + LogN(\overline{T_l} - T_{l,\min}, r \cdot \overline{T_l}) \qquad (4.1)$$

Where:

T_l - Travel time on link l

$T_{l.\min}$ - Minimal travel time on link l according to free flow speed

$\overline{T_l}$ - Average travel time on link l according to the operator

r - Ratio, determined by the travel time variability scenario

The dwell time functions were based on recommendations in the Transit Capacity and Quality of Service Manual (TCRP, 2003), which assumes that passengers' arrivals follow a Poisson distribution and the alighting process has a binomial form (as described in Chapter 3). At both trip ends, recovery times were calculated based on the 85th percentile of the trip travel times. These recovery times were then used as minimum requirements in determining the trip assignment for each bus vehicle.

For the sake of clarity most of the presented results will focus on the inbound direction, which is the dominant demand direction on the morning peak hour. Moreover, general simulation results (Sections 4.2 and 4.3) are presented for the moderate scenario – moderate demand and variability levels. Section 4.4 compares the results of different scenarios.

4.2 Bus mechanisms' distribution

The elementary requirement from every simulation model is to reflect the processes as it was designed. Figure 4.3 and Figure 4.4 show the dwell time and headway distribution, respectively. The dwell time distribution is right-skewed. The average dwell time is 40.5 seconds and the coefficient of variation is 0.54. These values are in correspondence with those found by previous studies (TCRP, 2003). Headways follow a normal distribution with a long right tail and a mean of 480 seconds, as expected. This might suggest that the form of the headway distribution is dictated more by dwell times (which follow normal distribution) than by running times (that follow lognormal distribution). This is perhaps because running times were randomized independently for each link and therefore over the entire route exhibit lower variability, as the random terms do not propagate.

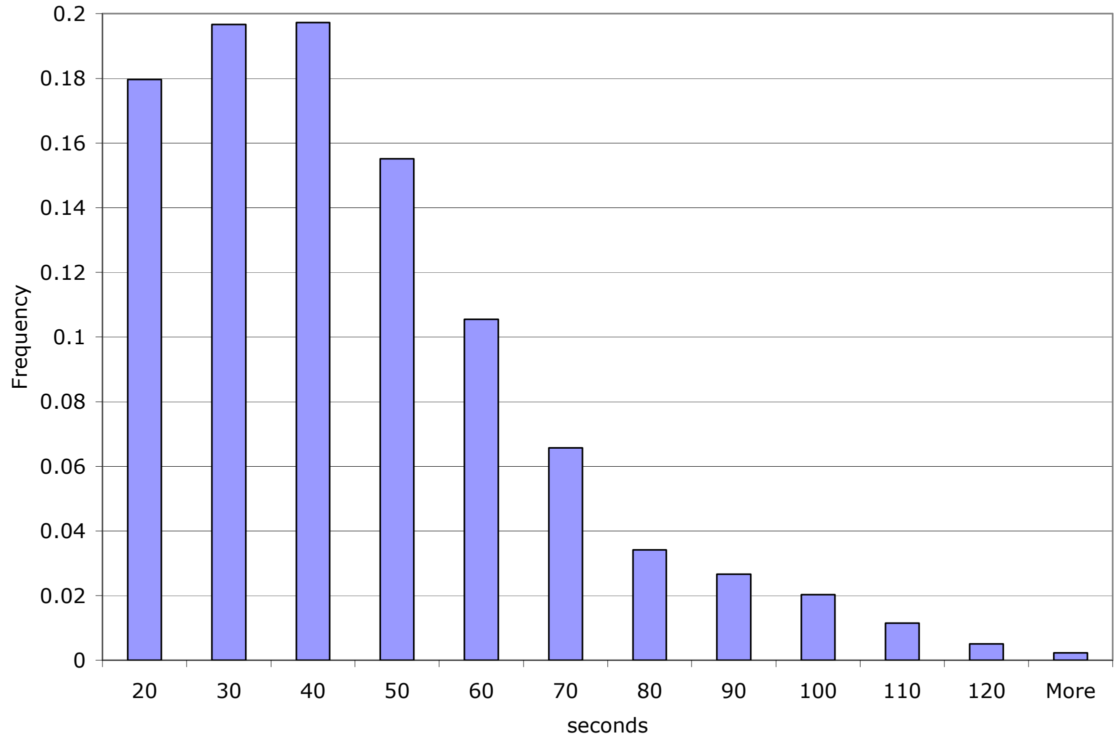

Figure 4.3: Histogram of the dwell time

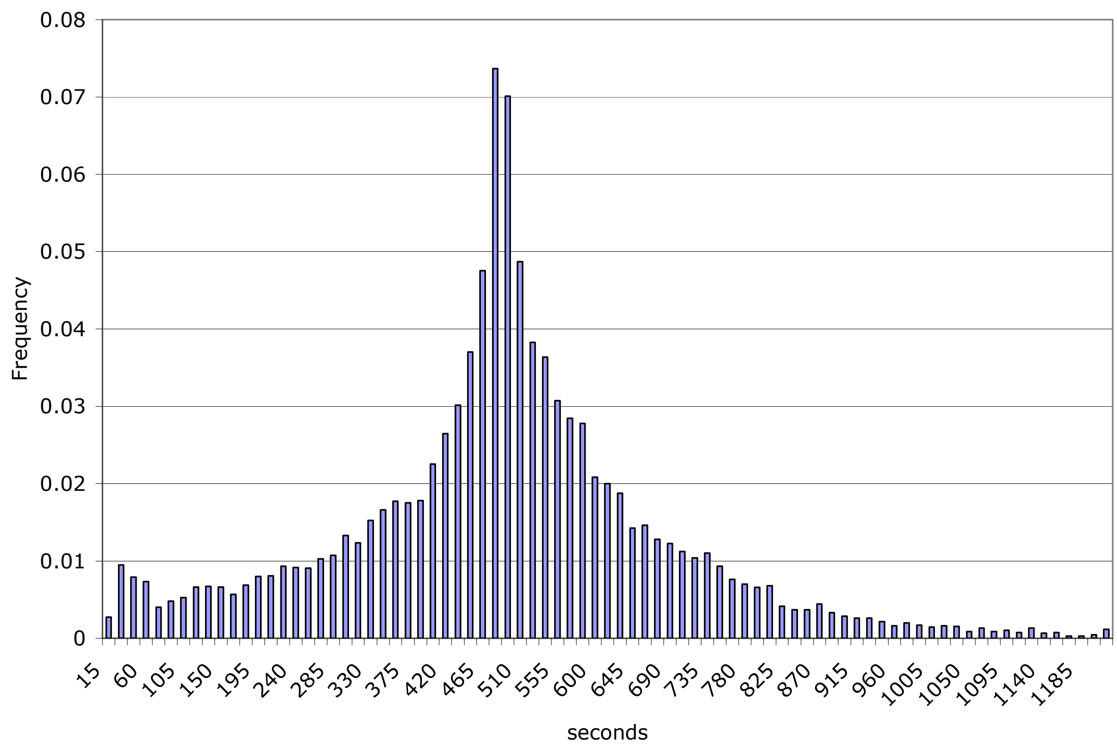

Figure 4.4: Histogram of the bus headways

The schedule adherence distribution (Figure 4.5) has a high dispersion - the coefficient of variation is 14.5. On average, the bus arrived at a bus stop 11 seconds before scheduled, yet the mode arrival time is between 15 and 30 seconds late. On a frequent service, the absolute deviation from schedule may be more important then being early or late. As figure 4.6 shows, the (absolute) deviation from schedule follows an exponential distribution and 60% of the deviations are smaller than quarter of the planned headway, which is also the average deviation. Moreover, 95% of the deviations are less than 0.75 times the planned headway and 1.5% of bus arrivals are more than headway away from their scheduled arrival.

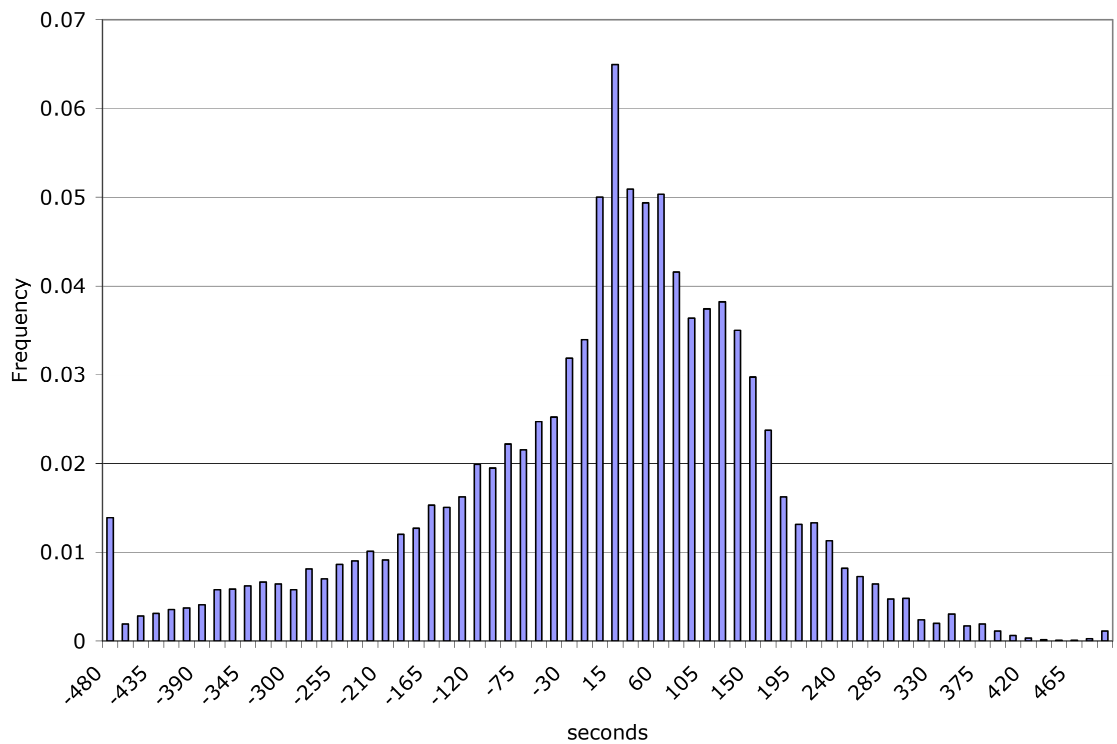

Figure 4.5: Histogram of the schedule adherence

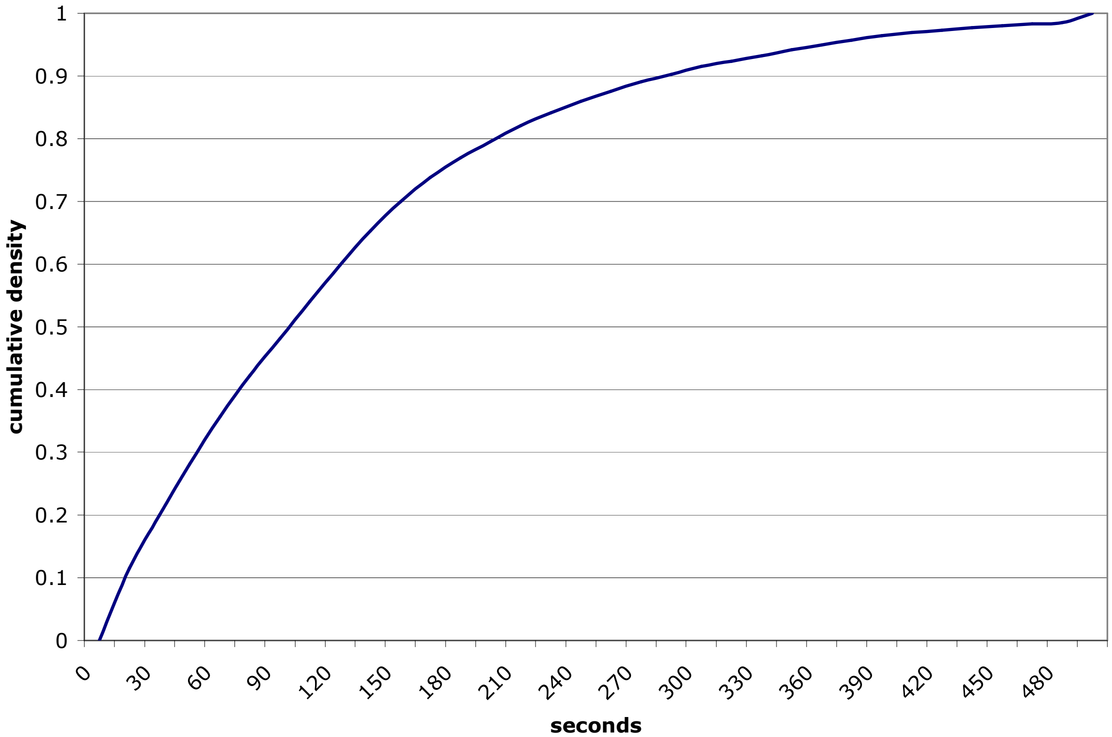

Figure 4.6: Cumulative distribution function of the absolute deviation from schedule

4.3 Service along the trip

A phenomenon in transit systems that may have significant impact on levels of service is the accumulation of variability in travel times as buses progress through their schedules. Figure 4.7 demonstrates the evolution of headway variability at the various stops along the inbound route. The observed increase in headway variability suggests that implementation of control strategies, such as headway-based holding of buses at time points may be useful for this line.

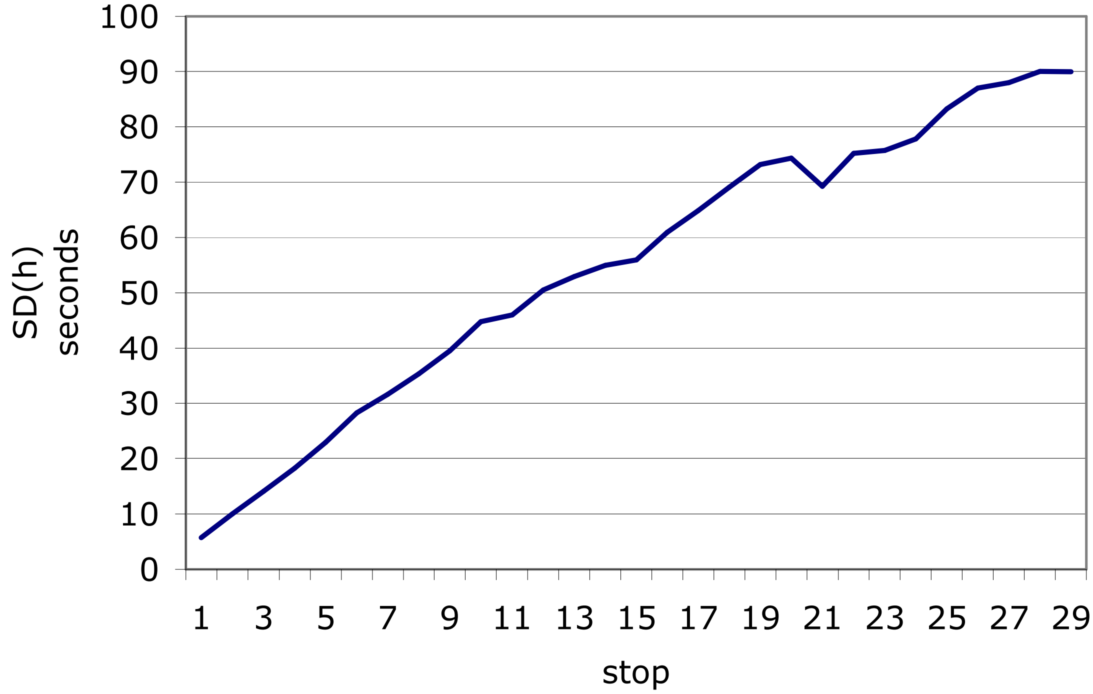

Figure 4.7: Standard deviation of headways (inbound route)

As the standard deviation of the headway increases along the route, the on-time performance statistic decreases – It dropped from 100% to 57% (Figure 4.8). Following the industry standard (Ceder, 2007), a bus was considered to adhere to schedule at a specific stop, if it arrived between one minute early and four minutes late compared to its scheduled arrival.

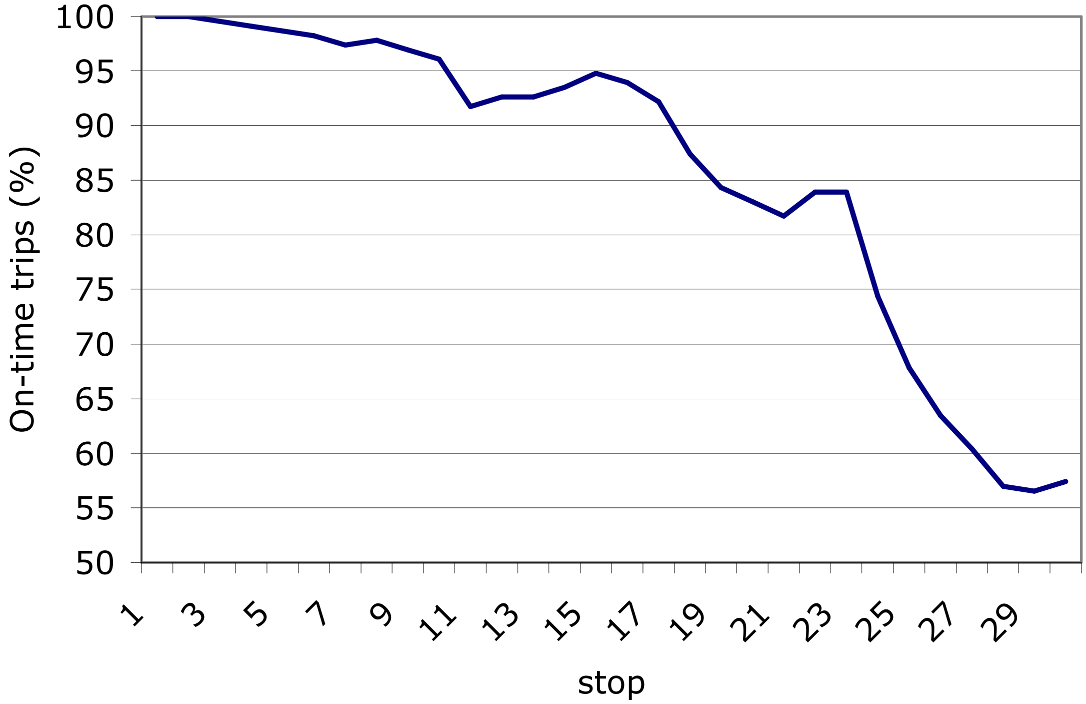

Figure 4.8: Percentage of on-time performance (inbound route)

The detailed representation of bus operations in the simulation allows performance evaluation ranging from the level of a single run to the overall system performance. At the most detailed level, Figure 4.9 presents a time-space diagram showing the trajectories of two selected buses (buses 12 and 13 out of the 16 assigned bus vehicles) in service on line 51 during the study period. The continuous lines are the simulated trajectories compared with the scheduled trajectories displayed by the broken lines. In the figure, both buses make three trips. It is ahead of schedule on its first trip, was increasingly late on the second and on time on the third. Recovery times between trips at both terminals are also apparent in the figure, as both buses conducted three sequential trips.

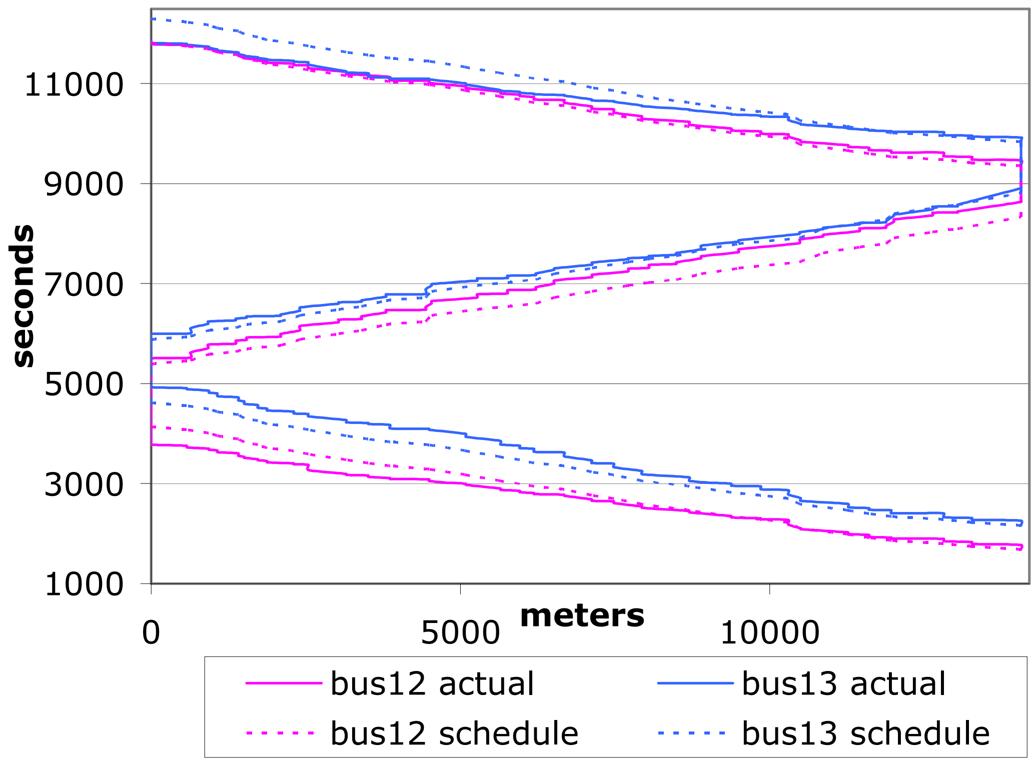

Figure 4.9: Time-space diagram vs. scheduled trajectory

The well-known bunching phenomenon (e.g. Abkowitz and Tozzi, 1987) is represented by the simulation as shown in Figure 4.10. Buses 12 and 13 were bunched together on their first trip, while buses 11 and 12 were bunched together on their third trip. In the extreme case, instead of the planned headway of 480 seconds, bus 11 arrived on the last trip 1300 seconds after bus 10, only 110 seconds before bus 12. Bus bunching occurs as a result of various stochastic processes involved with bus operations: early or late dispatching, changes in traffic conditions and the random nature of passengers' arrival. These stochastic variables cause the bus to have a shorter or longer headway than planned. The deviation from the planned headway tends to propagate, since the dwell time is demand-dependent and the demand is headway-dependent. The simulation reflects the reliability problems caused by the bus bunching and its escalating nature.

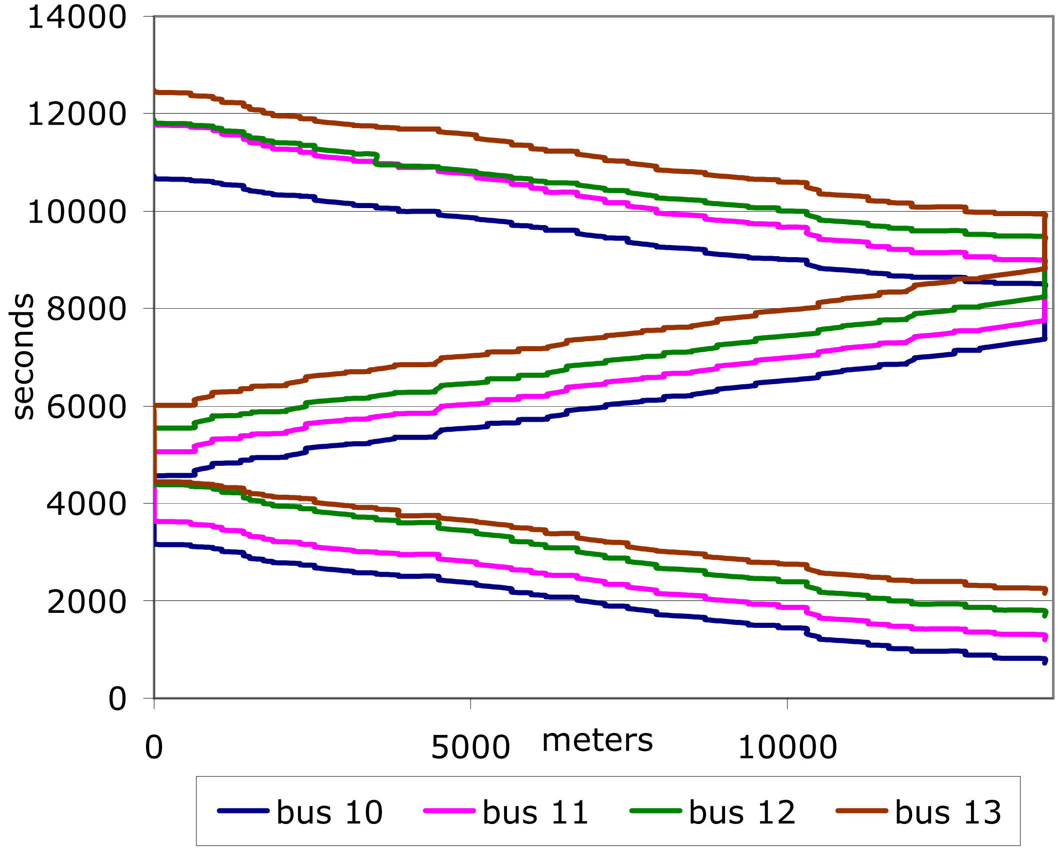

Figure 4.10: Time-space diagram of selected bus vehicles on service

Headway variability and bus bunching are also important causes for variability of load profiles. Figure 4.11 shows an example of the load profiles of the outbound route for two sequential bunched buses (the headway at the destination stop was two minutes) and the expected load profile for the planned headway. The load profile for the planned value was approved also by a simulation run with deterministic conditions (constant running times and dwell times). It can be seen that the actual load profile varied significantly from the one expected under deterministic conditions: the late bus with high headway had to pick up all the passengers that had accumulated, which resulted in longer dwell times and caused the following bus that had fewer passengers and therefore shorter dwell times to catch up with it. From the passenger point of view, being unable to board or riding over-crowded buses are sources for inconvenience.

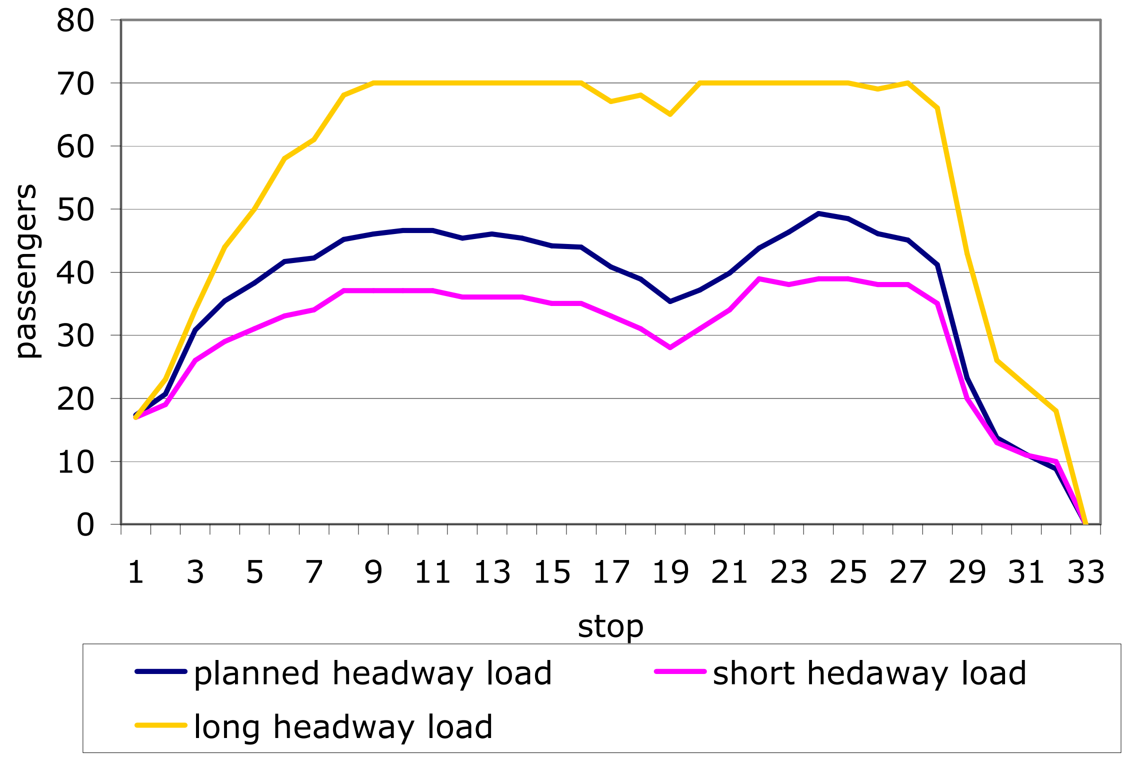

Figure 4.11: Load profile on bunched buses vs. expected load profile under planned headway (outbound route)

4.4 Scenarios comparison

Several system-level measures of performance may be calculated from the simulation outputs. Table 4.2 summarizes these measures for the various scenarios. A series of t-tests for all scenarios and system measures were performed under the null hypothesis that variability and demand levels are insignificant. Each t-test compared the results for a pair of scenarios for a specific system measure. Both factors, the demand level and the variability levels, were found to be significant factors ($p<.01$) for all system-level measures presented in the table, except for the number of passengers unable to board per stop that was affected only by demand level. In general, demand level factor has stronger significant values than variability level factor. The variability of headways is the main measure for evaluating transit reliability, in particular for short-headway services. The headway variability was calculated for each stop along the route. The reported statistics are the means across all stops in each direction. As expected, headway variability increased with the level of variability of running times between stops, but the magnitude of this trend varied significantly with the demand level, as shown in Figure 4.12.

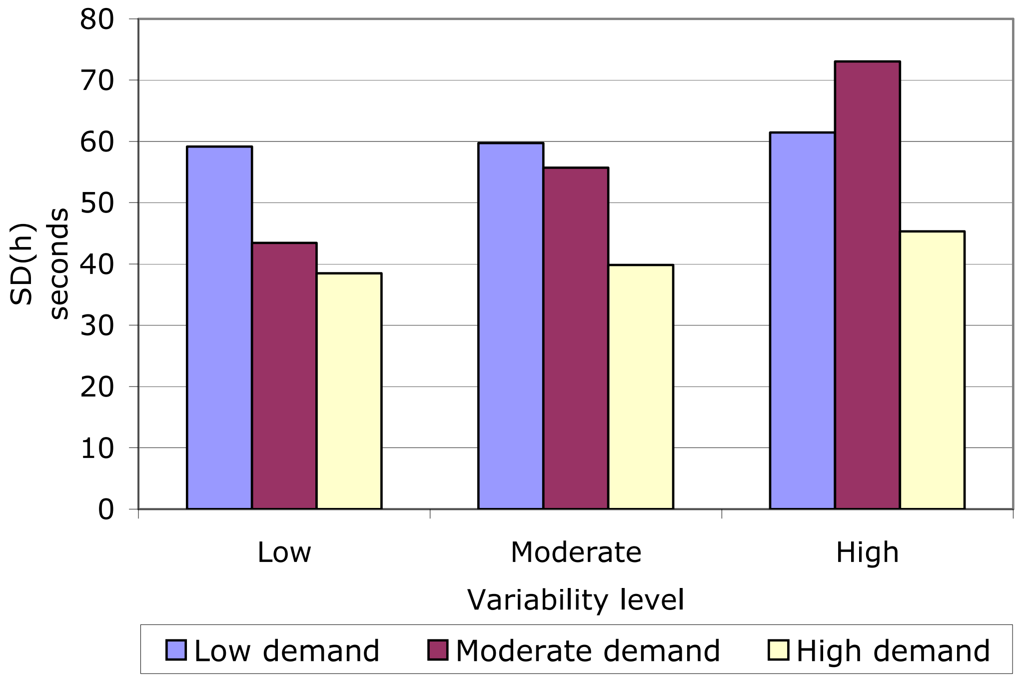

Figure 4.12: Average standard deviation of headway for inbound route at different scenarios of demand and variability levels

However, headway variability did not increase with demand level. This perhaps counter-intuitive result seems to derive from the high demand load. It is suggested that headway variability increases with demand level until a certain point because of the relation between the mean dwell time and the dwell time variability (since the passenger arrival process assumed to follow the Poisson distribution that has a variance that equals the mean). However, from a certain point the bus is too crowded to allow all waiting passengers to board. Since the dwell time depends on the number of boarding passengers and not the number of arriving passengers, dwell times decrease when buses are crowded.

In order to examine this explanation, an additional demand scenario of half of the observed demand profile was conducted. Figure 4.13 presents the relation between headway variability and the demand level. The results support the above-mentioned hypothesis: headway variability increases with the demand level for low demands, but decreases in higher demand levels.

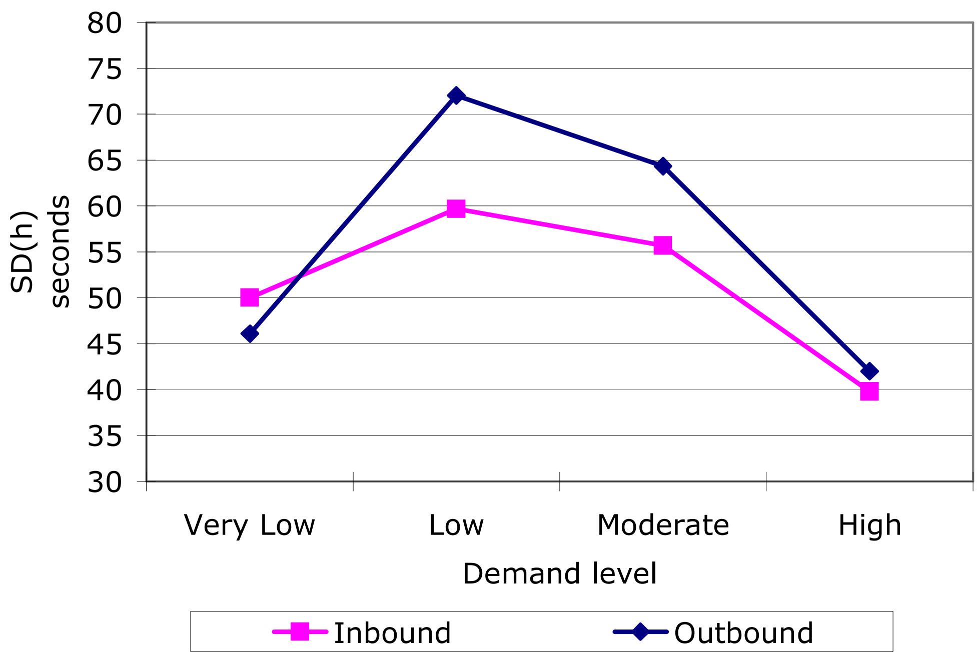

Figure 4.13: Standard deviation of headways as a function of the demand level (inbound route)

Table 4.2: Service measures of performance under various scenarios

Scenario		Measure of performance							
Demand	Variability	Inbound headway standard deviation (seconds)	Outbound headway standard deviation (seconds)	Inbound Passenger waiting time (seconds)	Outbound Passenger waiting time (seconds)	Bunching phenome-non (%)	On-time perform-ance (%)	Absolute Deviation from schedule (seconds)	Passengers unable to board per stop
Low	Low	59.14	69.46	243.64	245.03	22.40	54.5	142.13	0.42
Low	Moderate	59.69	72.03	243.71	245.40	25.12	54.91	141.81	0.39
Low	High	61.39	81.07	243.93	246.85	23.22	54.25	142.33	0.48
Moderate	Low	43.42	60.27	241.96	243.78	18.90	69.1	119.85	2.26
Moderate	Moderate	55.67	64.34	243.23	244.31	20.90	68.42	123.91	2.17
Moderate	High	80.05	87.41	246.67	259.91	21.39	68.97	201.44	5.45
High	Low	38.48	39.50	241.54	241.63	13.57	82.99	115.15	9.1
High	Moderate	39.83	42.02	241.65	241.84	12.27	83.84	107.51	9.49
High	High	45.28	53.96	242.14	243.03	14.35	82.79	112.00	8.69

The decrease in headway variability is explained by the difference between the number of arriving passengers and those that actually board the bus, due to over-crowding. Figure 4.14 shows the percentage of buses that depart from bus stops when the number of passengers on board exceeds the number of seats (50 seats) or when the capacity (70 passengers) was restricting, meaning that one passenger or more were left behind. At the moderate-demand scenario (which equals the observed demand profile), on 54% of the stop visits there were more passengers on-board than seats and on 18% some passengers were left behind. While the first is a measure of convenience to passengers, the second is a reliability measure that greatly affects passengers waiting time and dissatisfaction from the service.

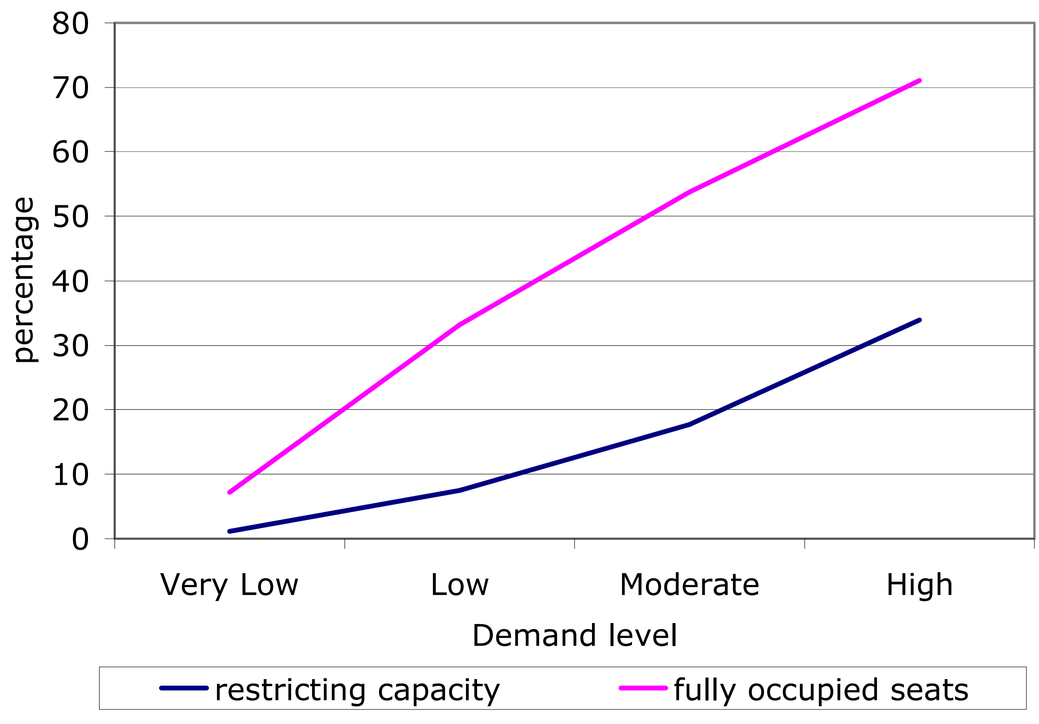

Figure 4.14: Percentage of fully occupied seats and restricting capacity at different scenarios of demand levels

The variability of the headway has a clear direct link to the bunching phenomenon. The percentage of bunched buses in the simulation was calculated by the share of buses that had headways less than 240 seconds, half of the planned headway. About one fifth of the buses were bunched with the field demand data. The demand level had the same influence as with the headway variability, while there was no significant role for running time variability.

Passenger waiting time is an important quality of service measure. Table 4.2 contains mean passenger waiting times for the outbound route that were calculated according to the traditional formula (Abkowitz and Tozzi, 1987):

$$E(w) = \frac{E(h)}{2} + \frac{V(h)}{2 \cdot E(h)} = \frac{E(h)}{2}(1 + CV_h^2) \quad (4.2)$$

Where:

$E(w)$	-	Average waiting time
$E(h)$	-	Average actual headway
CV_h	-	Coefficient of variation in headways (standard deviation/mean)

On-time performance is another important measure of service reliability. The reported values in Table 4.2 are averages over all trips and all stops. The relatively low on-time performance, except for the high-demand scenarios, is because of early arrivals, which calls for the implementation of schedule-based holding (especially because it decreases along the route, as shown in Figure 4.8). Absolute deviation from schedule is a non-dichotomy measure of schedule adherence of the average absolute difference between the actual arrival time and the scheduled arrival time. It has the advantage of direct proportion with the size of the deviations, but has the drawback of a possible inflection because of a rare extraordinary deviation.

The last system-level measure in Table 4.2 relates to the passenger load – the average number of passengers per stop that are unable to board the bus because it is over-crowded. Of course this measure increases with the demand level. Similarly to the relation between on-time performance and deviation from schedule, passenger left behind is an absolute average value of the binary measure presented on Figure 4.14.

4.5 Summary

The capabilities of Mezzo as an evaluation tool of transit operations and planning had been demonstrated with an application to a real-world high-demand line in the Tel Aviv metropolitan area with nine different demand and variability scenarios. The demonstration showed the implementation of bus operations and the kind of outputs that are generated by the simulation. The crude outputs can be aggregated at the bus stop, bus trip, bus line or up to system level in order to produce various measures of service. Moreover, BusMezzo has the capability to reconstruct phenomenon as propagation of headway variability and the descent of on-time performance along the route, bus bunching and the relation between headway variability and demand level. An evaluation case study of holding strategies, aimed to improve service reliability, is described in the next chapter, Chapter 5.

Chapter 5: Case study

The preceding chapter demonstrated BusMezzo capabilities through simulation results based on a real-world data. This chapter will present the implementation of real-time control strategies aimed to improve service reliability and operations. Following a short background, the literature on methods to determine the control strategy is reviewed. Then the scenarios design is described and the various results are presented and explained in sections 5.4-5.6, followed by a summary.

5.1 Background

The reliability of a transit service is one of the main factors that determines its level of service. The reliability of transit service is made up of two components: reliability of travel time and reliability of arrival time. The reliability depends heavily on the traffic conditions and on the type of service (e.g. right of way, traffic signal priority). There are a few transit operation strategies aimed to improve the reliability of transit service, holding strategies are among them (Abkowitz and Lepofsky, 1990). It is common that some stops are defined as time points, which means that the departure time from them is subject to policy constraints. Although hypothetically all stops might be defined as time points, a typical bus line includes only several time point stops (such as main transfer and CBD stations).

The literature distinguishes between two holding strategies: schedule-based and headway-based. Schedule-based holding enforces buses that arrive early to depart on their scheduled time. The difference between the mean arrival time and the scheduled time is known as slack size. The equivalent mathematical definition is:

$$ET_{ijk} = \max(ST_{ijk} + s_{ij}, AT_{ijk} + DT_{ijk}) \quad (5.1)$$

Where:

ET_{ijk} - Exit (departure) time for line i on trip k from stop j

ST_{ijk} - Scheduled arrival time for line i at stop j on trip k

s_{ij} - Slack size for line i on trip k at stop j

AT_{ijk} **-** Actual arrival time for line i on trip k at stop j

DT_{ijk} - Dwell time for line i at stop j on trip k

Headway-based holding enforces that the headway between two sequential buses will not be smaller than a pre-determined minimal value. The equivalent mathematical definition is:

$$ET_{ijk} = \max(AT_{ij,k-1} + h_{ij}^{\min}, AT_{ijk} + DT_{ijk}) \tag{5.2}$$

Where:

$h_{ij}^{\min}$ - Minimal headway allowed for line i at stop j

Headway-control strategies are intended for short-headways, when maintaining even headways reduces passengers waiting time. Schedule-control strategies are more likely to be useful as headways are longer and passengers tend to follow the schedule (Strathman et al. 1993). A bus stop that is controlled by a holding strategy is known as a time point stop.

There are three main decisions involved with implementing holding strategies: number of time points, location of time points and the slack size/minimal headway. The following section will review the literature regarding methods to implement holding strategies.

5.2 Literature review

A review of the literature that deals with methods to implement holding strategies revealed two distinct types of studies in the area: (1) analytical models that formulate the holding problem as an optimization program, mostly during the 1980's; (2) simulation models that draw rules out of the simulation results. It is important to note that there is no clear classification between the two types, some works developed analytical models and then evaluated them using a simulation tool. On one hand, analytical models are unable to represent fully the stochastic nature of the problem (caused both by journey time and demand pattern); On the other hand, simulation models do not result in a generalized method to confront the problem. The following presents the main methods to determine the holding strategy components.

An early attempt to set a general rule regarding where to locate time points and the slack size was made by Lesley (1975). A simulation model called SIMBUS was used to calculate the coefficient of variance ('reliability index') at each bus stop along the route. The study assumed that buses are dispatched according to schedule and suggested to locate time points where the reliability index is more than twice the average value on the line. The recommended slack size was found to be:

$$s_{ijk} = \overline{AT_{ijk}} + \overline{DT_{ijk}} + \sigma_{h_{ij}} \tag{5.3}$$

Where:

s_{ijk} - Slack size for line i on trip k at stop j

$\overline{AT_{ijk}}$ - Average actual arrival time for line i on trip k at stop j

$\overline{DT_{ijk}}$ - Average dwell time for line i at stop j on trip k

$\sigma_{h_{ij}}$ - Standard deviation of the observed headway for line i at stop j

Several studies searched analytically for threshold criteria to implement holding control strategies and the derived holding time. An analytical model was developed by Turnquist and Blume (1980). The authors developed analytically the optimal solution for two extreme cases of headway-based time point (complete dependence or no dependence between successive headways). They assumed that passengers arrive randomly ($H_i \leq 10$ min). This resulted with the two following conditions:

$$\text{(a)} \quad \frac{\sigma_{h_{ijk}}}{H_i} > \frac{0.5 \cdot \gamma_{ijk}}{1-\gamma_{ijk}} \tag{5.4}$$

$$\text{(b)} \quad 0 \leq \gamma_{ijk} < 0.5 \tag{5.5}$$

Where:

$$\gamma_{ijk} = \frac{O_{ijk}}{\sum_{l=j+1}^{N_i} B_{ilk}} \tag{5.6}$$

H_i - Planned headway for line i

O_{ijk} - Occupancy on line i on arrival at stop j on trip k

B_{ilk} - Number of boarding passengers on line i at stop l on trip k

N_i - Number of bus stops on line i

These two conditions can serve as initial sort for determining the location of time points: if a stop complies with both conditions- then it should be a time point; if both conditions fail- then it should not be a time point; if it complies with only one of the conditions, then it requires an additional analysis. Because the research treated two extreme scenarios, the minimum headway for the holding control is given as a range:

$$\frac{(1-2\cdot\gamma_{ijk})}{(1-\gamma_{ijk})}\cdot H_i \le h_{ij}^{\min^*} \le \frac{(1-1.5\cdot\gamma_{ijk})}{(1-\gamma_{ijk})}\cdot H_i \qquad (5.7)$$

The left expression is the optimal if there is perfect dependency between successive headways and the right expression is the optimal if successive headways are independent.

Another analytical attempt was made by Abkowitz and Engelstein (1984). The authors used a three steps approach: First, they determined the mean and variation of running time, headway variation and passenger waiting time based on field-data and simulations and under the assumption of on-time departures from the origin. Secondly, they developed analytical models for headway-based holding and schedule-based holding:

(a) headway-based: the objective function is the expected total waiting time on route (upstream, on-board and downstream):

$$\sum_{l=1}^{j-1}(B_{ilk}\cdot\overline{W_{ilk}})+O_{ijk}\cdot d(s_{ijk})+\sum_{l=j}^{N}(B_{ilk}\cdot\overline{W_{ilk}}) \qquad (5.8)$$

W_{ijk} - Waiting time at stop j for trip k of line i

$d(s_{ijk})$ - Expected delay at the time point stop j for trip k of line i for the slack size of s_{ijk} (in minutes)

(b) schedule-based: rank stops in descending order according to their E.R. (effective ratio) score:

$$E.R._{ij} = \frac{\sigma_{T_{ij}}\cdot\sum_{l=j}^{N}B_{ilk}}{O_{ijk}} \qquad (5.9)$$

Where:

T_{ij} - travel time from stop $j-1$ to stop j on line i

Finally, the solution was evaluated using simulation. It was found that for different patterns of demand, time points were located just before a group of stops with high-demand profile.

Eberlein et al. (2001) formulated an analytic model with a heuristic search for the optimum assuming real-time information. The model is completely deterministic, but the authors claim that since the holding effect is short in nature, the solution for the deterministic problem is a reasonable approximation. The objective is to minimize total passenger waiting times (equivalent to minimizing headway variation) for a holding decision regarding vehicle v at stop j :

$$\min f_{v,j}(d) = \sum_{l \in V_m} \sum_{m=j}^{N} \lambda_m \cdot (d_{l,m} - d_{l-1,m})^2 \tag{5.10}$$

Where:

V_m - The impact set of m sequential vehicles

$d_{v,j}$ - Departure time of vehicle v from stop j

The authors found that the vast majority of the effect is captured for an impact set of m=3 ($V_m = \{v, v+1, v+2\}$), which means that holding only affects the couple consecutive vehicles. One of the constraints was that if a vehicle is already late for the next trip on its schedule, then it will not be held. The initial step determined the departure time of vehicle v so that the headway variation along the line is minimal. Then the problem is solved through an iterative process that finds the departure times for all other vehicles at stop j. The departure times change incrementally till the difference between iterations is below a threshold value. The model was evaluated through a deterministic simulation, which found that the best place to locate a time point is at the origin station. In addition, the cost reduction decreases with the stop number and there are no significant benefits for additional time points.

Another possible approach is based on costs – the objective function sums up all the costs that might differ between the evaluated operation alternatives. Wirasinghe and Liu (1995) developed an analytical model with an objective function of the mean total cost with all components expressed as function of slack times:

$$E(C)=E(C_{w0})+\sum_{i=1}^{n-1}[E(C_{wj})+E(C_{raj})+E(C_{dj})]+E(C_{ran})+E(C_{dn})+E(C_{o}) \qquad (5.11)$$

Where:

C - Total cost

C_{wj} - Passenger waiting time cost incurred at stop j

C_{raj} - Riding time cost in link j for alighting passengers at stop j

C_{dj} - Delay penalty at stop j

C_{o} - Operation cost for one trip

The function was minimized through dynamic programming. Every stop is a time point candidate and the selection is done according to a threshold criterion for the fraction of held buses at the bus stop. Therefore, the model does not capture inter-effects between time points. The selected time points served as input to the simulation and the slack-times were re-evaluated. The research found that holding control prevents the variability of arrival times to increase continuously. However, the model only deals with a single run by assuming that the numbers of boarding and alighting passengers are constant and that no passenger misses the bus (no capacity constraints). In addition all link travel times follows a single gamma distribution, which was applied also for the departure from the origin.

In a follow-up study, Liu & Wirasinghe (2001) developed a simulation model with a cost-based approach. The Optimization process was made up of three steps: semi-enumeration that limits the feasible set followed by heuristic search rules and evaluation in descending order. It was assumed that passengers arrive according to a compound non-homogenous Poisson, link travel times follow a gamma distribution and so did dwell time coefficients. In addition, alighting passengers were estimated through a binomial distribution and buses were dispatched by a lognormal or a gamma distribution. The simulation set the origin stop as a time point and was tested with a demand profile with three distinguished sections: (a) only boarding; (b) boarding and alighting; (c) only alighting. The total cost objective function was:

$$C = \sum_{j=1}^{N}\sum_{k=0}^{K}(C_{wj,k} + C_{dj,k} + C_{pj,k}) + C_{ok} \tag{5.12}$$

Where:

$C_{wi,j}$ - Waiting time cost for boarding passengers at stop j for trip k

$C_{di,j}$ - Delay cost to thorough passengers at stop j for trip k

$C_{pi,j}$ - Late/early penalty for all alighting passengers at stop j for trip k

C_{oj} - Operation cost for trip k

It is important to note that the number of time points is given as an input to the simulation. The simulation analysis concluded that in case of two time-points, most included one intermediate point at the boarding section and one in the parallel section. No time point was located in the alighting section. It was also found that as the number of time point increases the optimal slack time decreases to zero.

Some researchers used simulation models to evaluate various holding strategies. Vandebona and Richardson (1986) used the TRAMS simulation to evaluate different severity of holding. The simulation generated vehicles in the origin according to a truncated normal distribution and scheduled timetable is determined by the mean travel times between stops. The simulation tested the effect of different slack sizes in terms of travel time standard deviation on the generalized passenger travel time (the sum of mean travel time and weighted mean waiting time). It was found that the optimal slack size is with zero offset from the timetable.

An additional simulation analysis was conducted by Senevirante (1990), who developed Bus-Monitor, a microscopic time-based simulation. The simulation generated boarding and alighting passengers according to a normal distribution in high-demand stops and Poisson distribution in low-demand stops. The contribution of a passenger to the dwell time followed a gamma distribution and travel times followed a normal distribution. The simulation model was limited to the representation of constant headways. Senevirante found that the relation between the standard deviation of the headway and the number of time points is a second degree polynomial. Therefore beyond a number of time points, the marginal effectiveness of an additional time point is negative. Time points were located in the proceeding stop of a point where the standard deviation of the headway exceeded 60 seconds and it showed to have a decreasing impact over time (from trip to trip).

Fu and Yang (2002) developed SimTransit and compared one-headway vs. two-headway (both preceding and following headways) based holding control. The simulation assumes that passengers arrive randomly and all link travel times follow a single normal distribution (without explicit representation of general traffic and traffic signals). The evaluation included several performance measures and concluded that if one time point is to be set then it should be located at a high boarding demand stop and close to the middle of the line. Compared with all-stops, no-stop and one-stop control, two-stop control was found to have the optimal performance measures (terminal + high boarding demand near the middle). The optimal threshold headway to provoke a holding action is in the range of:

$$0.6 \cdot H_i \le h_{ijk}^{\min^*} \le 0.8 \cdot H_i \tag{5.13}$$

An important drawback of this work is that it ignores inter-effects between time points.

A comparison between holding control strategies that relies on local information to APTS-based strategies was conducted by Dessouky et al. (2003). The simulation (AweSim) assumes random passengers arrival, gamma distribution of dwell time coefficients and lognormal distribution of travel times. The simulation received as an input the time point location (a transfer station) and returned the optimal slack size as output for a given holding strategy. It concluded that the best holding control strategy was the global optimized strategy, which is also the most technology-based. The objective function of this strategy found the optimal time for bus i to departure from a given stop while minimizing the total passenger waiting time:

$$ET_v = \underset{t=t\_now, FA_1, \dots FA_m}{\arg} \{Min[\max(0, FO_v(t - \max(ST_v, t\_now))] + \sum_{b|FA_j<t} (t - FA_b) \cdot TP_{bv} +$$
$$+ \sum_{b|FA_b>t} (FA_{l(v)} - FA_b) \cdot TP_{bv} + \sum_S E(FB_s)[\max(0, FA_{v,s|ET_v=t} - ST_{v,s})]\} \tag{5.14}$$

Where:

ET_v - Actual exit (departure) time for bus v from current stop

t_now - Current time

FA_v - Forecast arrival time of bus v at current stop

FO_v - Expected number of passenger on bus v at current stop

ST_v - Scheduled departure time for bus v at current stop

b - Index of a connection bus approaching the stop ($b = 1,...,m$)

TP_{bv} - Expected number of transferring passengers from bus j to bus v

$l(v)$ - Index of the next bus arrival after bus v

S - set of subsequent bus stops for bus v ($S = \{j+1, j+2,..., N\}$)

FB_s - Expected number of boarding passengers at subsequent stop s for bus v

$FA_{v,s|ET_v=t}$ -Forecast arrival time of bus v at subsequent stop s given the actual departure time at the current stop is t

The expression calculates the delay caused to passengers on-board, waiting time for transfer passengers from buses that arrive prior to bus i, waiting time for transfer passengers from buses that arrive later than bus i and waiting time of passengers at downstream stops, respectively. This strategy requires forecast arrival times of connecting buses, forecast of passengers arrival and considers net change and change in downstream stops in terms of waiting time due to holding.

Table 5.1 summarizes the reviewed studies in terms of the holding strategy applied (schedule-based/headway-based), the research tool that was used and other assumptions made. The table does not present the outcomes of the researchers because of their complexity.

Table 5.1: Summary of researches about methods to determine holding strategies

Research	Holding strategy	Research method	Important assumptions
Lesley (1975)	Schedule	Numerical simulation	On time dispatching
Turnquist and Blume (1980)	Headway	Analytical	
Abkowitz and Engelstein (1984)	Schedule, Headway	Empirical, Analytical, Numerical simulation	On time dispatching, independence between bus lines
Vandebona and Richardson (1986)	Schedule	Simulation	Dispatching ~ truncated normal
Senevirante (1990)	Headway	Simulation	
Wirasinghe and Liu (1995)	Schedule	Analytical	Number of Boarding and alighting passengers is constant, no capacity constraint
Liu & Wirasinghe (2001)	Schedule	Analytical, Simulation	Special demand pattern
Eberlein et al. (2001)	Headway	Analytical	Completely deterministic
Fu and Yang (2002)	Headway	Simulation	
Dessouky et al. (2003)	Headway	Numerical simulation	

There is a consensus in the holding strategies research that headway-based holding is expected to be more effective in short-headway service, while schedule-based holding suits long-headway service (since passengers tends to coordinate their arrival to the schedule). There are two common results in regards to the optimal location of time point stop: origin stop and just before a chain of high-demand stops. Those results were used in the design of the case study scenarios, as described in the next section.

5.3 Scenarios' description

Following the common distinction in the literature, the case study examined two control strategies: headway-based holding and schedule-based holding. The case study implements two holding control strategies on line 51 in the Tel Aviv metropolitan area, in addition to the base scenario, with no control strategy, which was described on Chapter 4. The case study includes full-factorial analysis of control strategies, demand levels and variability levels. A total of 27 scenarios were simulated and as with the no control scenarios - for each scenario 10 simulation runs were conducted for a four hour period between 6AM and 10AM. The execution time for each run was about 50 seconds, and so the additional 180 runs took about 150 minutes.

The number and location of time points, as well as the threshold criteria and slack size or minimal headway were determined according to common values and methods found in the literature review. In order to have comparable scenarios, it was decided to have the same number and location of time points under both strategies. Several studies (Abkowitz & Engelstein 1984, Turnquist & Blume 1980, Wirasinghe & Liu 1995, Liu & Wirasinghe 2001) that conducted either analytical models or simulation models found that time-point stops should be located just before high-demand stops. This method was applied on the boarding profiles (see section 4.1) and determined the location and number of time point stops on both directions. It resulted with three time point stops (7, 13 and 21) on the inbound route and two on the outbound route (8 and 19).

After the number and location of time-points were set, the holding time is left to be determined. Following the results of previous studies (Turnquist & Blume 1980, Fu & Yang 2002), headway-based holding was implemented with a minimal headway of 0.8 times the scheduled headway ($h_{ij}^{\min} = 0.8 \cdot H_i = 384\sec$). Schedule-based holding was simulated with a slack size of zero, which implies that the bus does not depart from time point stop before it scheduled time, based on the literature review (Vandebona & Richardson 1986, Liu & Wirasinghe 2001).

Table 5.2 summarizes the design of the case study scenarios and the levels of the various factors. The results of the nine no control scenarios were described in sections 4.2-4.4, while the results of the holding scenarios and their comparison with the base scenarios are described in the following sections.

Table 5.2: Factors and their levels in the case study

Factors	Levels
Control strategy	No control, headway-based control ($ET_{ijk} = \max(AT_{ij,k-1} + 0.8 \cdot H_i, AT_{ijk} + DT_{ijk})$), schedule-based control ($ET_{ijk} = \max(ST_{ijk}, AT_{ijk} + DT_{ijk})$). [stops 7,13,21 on inbound route, stops 8,19 on outbound route]
Passenger demand	80%, 100%, 120% of observed demand profile
Travel time variability	80%, 100%, 120% of mean travel time

5.4 System-level measures

System-level measures were calculated for the holding control scenarios and are presented in tables 5.3 and 5.4. Most of those measures are significantly different compared with those of the no control scenarios (table 4.2). As for the demonstration, a series of t-test were conducted for each pair of scenarios, for every system measure, under the null hypothesis that variability and demand levels are insignificant. As for the no control scenarios, demand level and variability levels were significant factors for all system-level measures ($p<.01$), except for the number passengers left behind that had only demand level as a factor. In all cases, the ANOVA resulted in higher significant values for the demand factor than for the variability factor.

Holding strategies are aimed to improve transit reliability as measured by various measures. F-tests and t-tests were performed in order to check the null hypothesis that control strategy did not result in different values of system measures. The variability of the headway is a key measure in any reliability evaluation since it determines passenger waiting times and the bunching phenomenon. The standard deviations of the headway under the three control strategies are presented in Figure 5.1. The average headway standard deviation (for both directions) under no control is 60 seconds, significantly ($F>1.20$, $p<.001$) higher than under headway or schedule control, 48 seconds and 52 seconds, respectively. Moreover, the headway variation is significantly lower under headway control than under schedule control for the outbound route ($F>1.29$, $p<.001$). One of the consequences of high headway variability in terms of level of service is the bunching phenomenon. A pair of buses was defined bunched if the headway between them was smaller than half of the planned headway. The incidence of bunching phenomenon decreased up to 70% due to control strategies implementation. The percent of bunched buses was significantly ($F>45$, $p<.001$) lower under schedule control (11%) than under no control (21%) and the lowest under headway control (Figure 5.2). These results are in correspondence with the trend for headway standard deviation. Interestingly, the differences in the incidence of bus bunching have a bigger magnitude than those of the headway variability. Another system-level measure is called service regularity - the percentage of headways that are between 50% and 150% of the planned headway (Nakanishi, 1997). The regularity score increased from 86% with no control to 90% when headway control was implemented and as high as 96% under schedule control.

The on-time performance (percentage of buses arrival between one minute early and four minutes late compared with their schedule) was improved significantly ($F>95$, $p<.001$) from 68% to 75% under headway control and 79% following the schedule control implementation (Figure 5.3). The average deviation from schedule (Figure 5.4) decreases significantly ($F>5.9$, $p<.01$) from 123 seconds to 119 seconds and 91 seconds following the implementation of headway and schedule control strategies, respectively. Differently from all other results, the demand level was not a factor for the average deviation from schedule under control strategies scenarios.

One of the expected results of lower service variability is that passenger load would be more evenly distributed between buses. However, the results do not show a decrease in the percentage of buses that depart from stops in full capacity or in the average number of passengers that were left behind because of over-crowded buses.

The implementation of control strategies improved the level of service, as indicated by various measures. In particular, the headway-based strategy reduced dramatically the headway variability and the bunching phenomenon, while schedule-based strategy improved the on-time performance measures. The two following sections will track the source of these results: the change in service attributes along the bus trip and in the distributions of service components due to holding strategies.

Table 5.3: Service measures of performance under various headway control scenarios

Scenario		Measure of performance							
Demand	Variability	Inbound headway standard deviation (seconds)	Outbound headway standard deviation (seconds)	Inbound Passenger waiting time (seconds)	Outbound Passenger waiting time (seconds)	Bunching phenomenon (%)	On-time performance (%)	Absolute Deviation from schedule (seconds)	Passengers unable to board per stop
Low	Low	37.51	47.24	241.47	242.32	6.70	68.42	111.85	0.45
Low	Moderate	43.66	53.48	241.99	242.98	6.86	58.82	113.73	0.37
Low	High	48.58	52.70	242.46	242.89	6.29	58.45	116.74	0.35
Moderate	Low	31.75	32.51	241.05	241.10	5.92	77.13	107.16	2.92
Moderate	Moderate	42.52	53.72	241.88	243.01	6.36	74.78	119.46	2.80
Moderate	High	48.59	63.41	242.46	244.19	5.67	75.22	159.40	2.96
High	Low	27.22	38.33	240.77	241.53	2.18	87.62	98.24	9.96
High	Moderate	31.09	47.00	241.01	242.30	2.12	87.62	105.21	9.96
High	High	46.87	58.18	242.29	243.53	4.68	82.18	163.49	9.61

Table 5.4: Service measures of performance under various schedule control scenarios

Scenario		Measure of performance							
Demand	Variability	Inbound headway standard deviation (seconds)	Outbound headway standard deviation (seconds)	Inbound Passenger waiting time (seconds)	Outbound Passenger waiting time (seconds)	Bunching phenome-non (%)	On-time perform-ance (%)	Absolute Deviation from schedule (seconds)	Passengers unable to board per stop
Low	Low	42.49	43.78	241.88	242.00	11.25	62.14	93.47	0.30
Low	Moderate	53.86	43.88	243.02	242.01	11.93	63.91	93.52	0.44
Low	High	55.34	73.57	243.19	245.64	13.77	62.42	110.56	0.47
Moderate	Low	44.19	45.77	242.03	242.18	8.33	73.91	93.04	3.55
Moderate	Moderate	47.93	55.93	242.39	243.26	11.29	78.95	91.38	3.55
Moderate	High	44.23	56.50	242.04	243.33	13.05	77.13	110.95	3.30
High	Low	30.11	31.11	240.94	241.01	7.79	87.13	97.85	9.23
High	Moderate	32.67	43.74	241.11	241.99	8.55	86.19	99.61	8.37
High	High	46.27	46.45	242.23	242.25	9.70	85.65	101.88	9.43

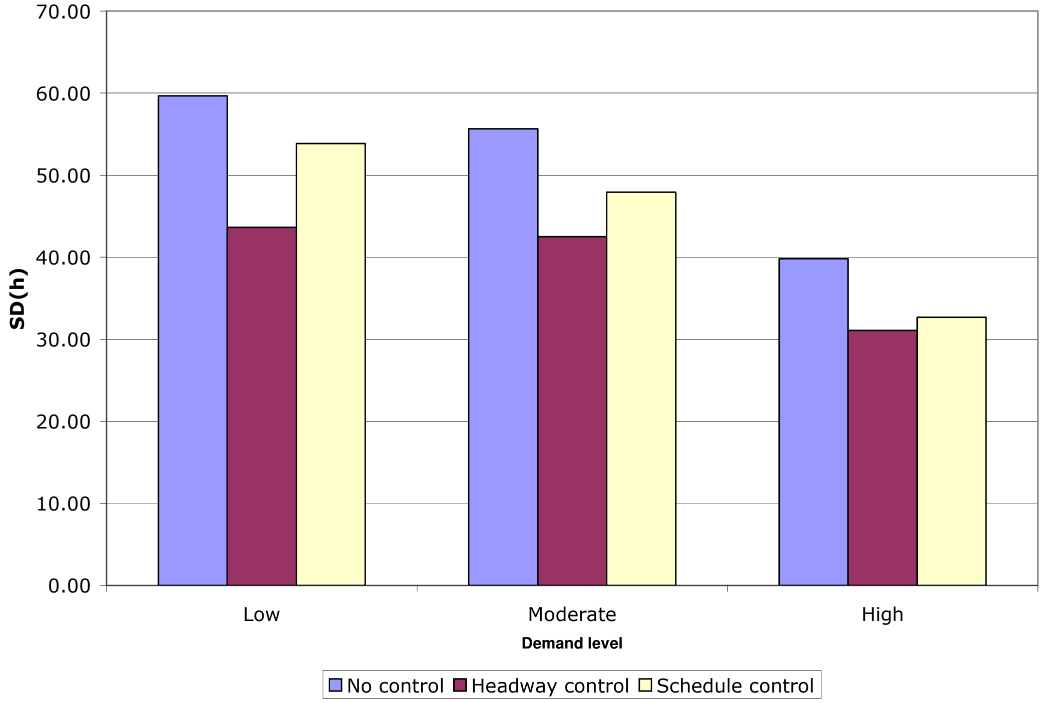

Figure 5.1: Average standard deviation of headway (inbound route)

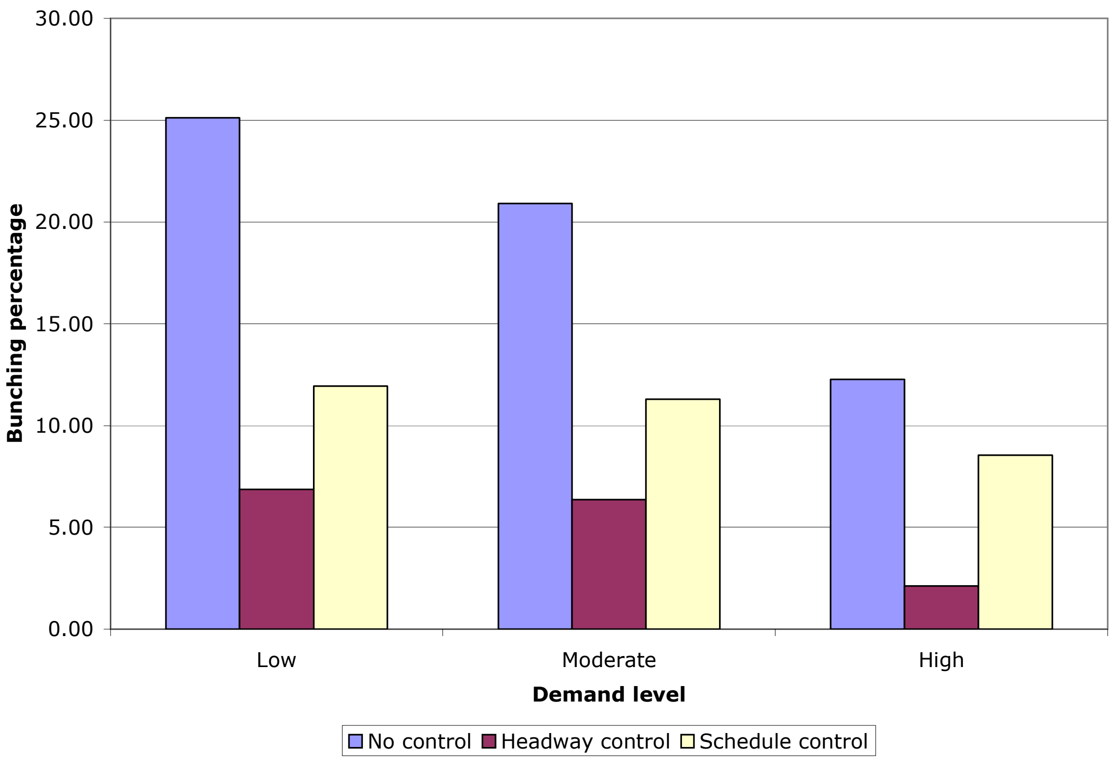

Figure 5.2: Percentage of bunched buses

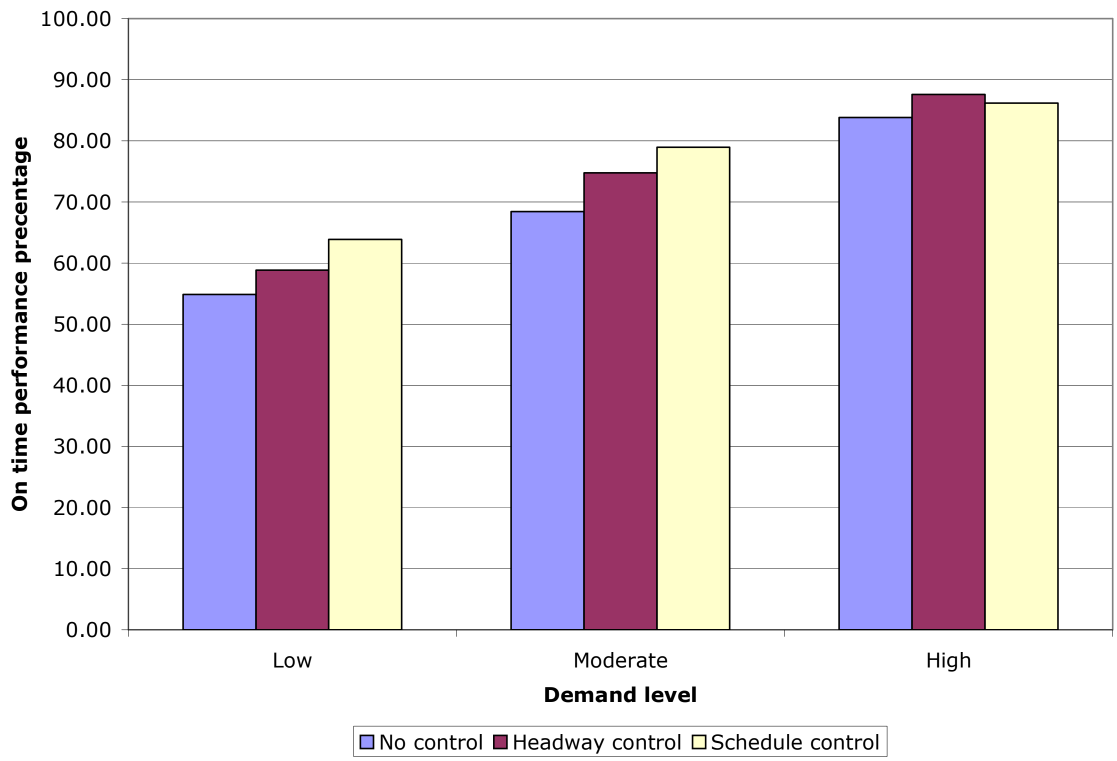

Figure 5.3: Percentage of on-time performance

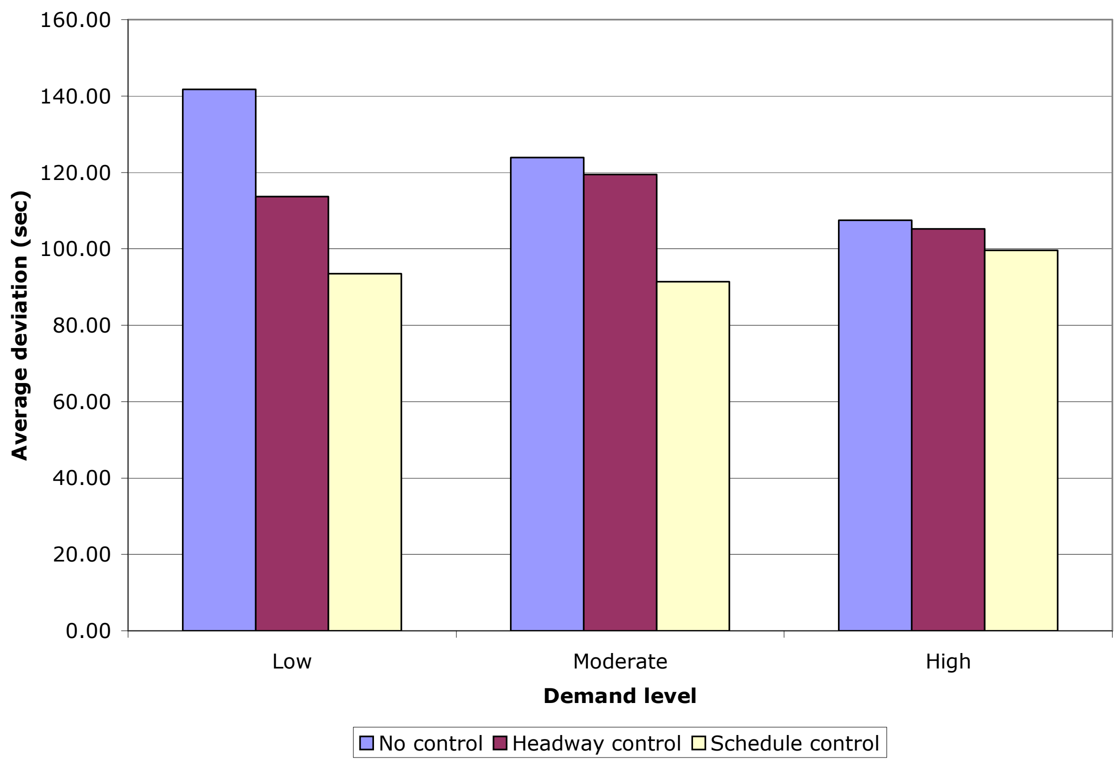

Figure 5.4: Average deviation from schedule

5.5 Service along the trip

Holding strategies are carried out on specific points along the bus route. Therefore, their effect on the performance of service attributes can be observed and ascribed along the bus route. Of course, the number and locations of time points has substantial role in determining the exact effect, but some general conclusions can be drawn.

Figures 5.5 and 5.6 present representative outbound trajectories of individual trips when holding controls are implemented. These graphs should be viewed with comparison to the time-space diagram when there is no control (Figure 4.10). The two time point stops are noticeable by the vertical jump in the graph for some of the buses. For example, bus 13 in Figure 5.5 dispatched exactly planned-headway after bus number 12. As it progressed along the route, it came closer to the preceding bus. The time point at stop number 8 was activated based on headway control for both buses, but it did not prevent the bus bunching further on the route. The actual headway between the two buses at stop number 21 was only 177 seconds (less than 37% of the planned-headway) and therefore the second time point was also activated for bus 13. The holding of the bus till the pre-determined criteria (in our case – 0.8 times the planned-headway) prevents the continuation and escalation of the bunching phenomenon. Note that this strategy does not take into account the schedule. At the extreme case, it may be optimal to have constant headways on shifted schedule without any link to the original schedule.

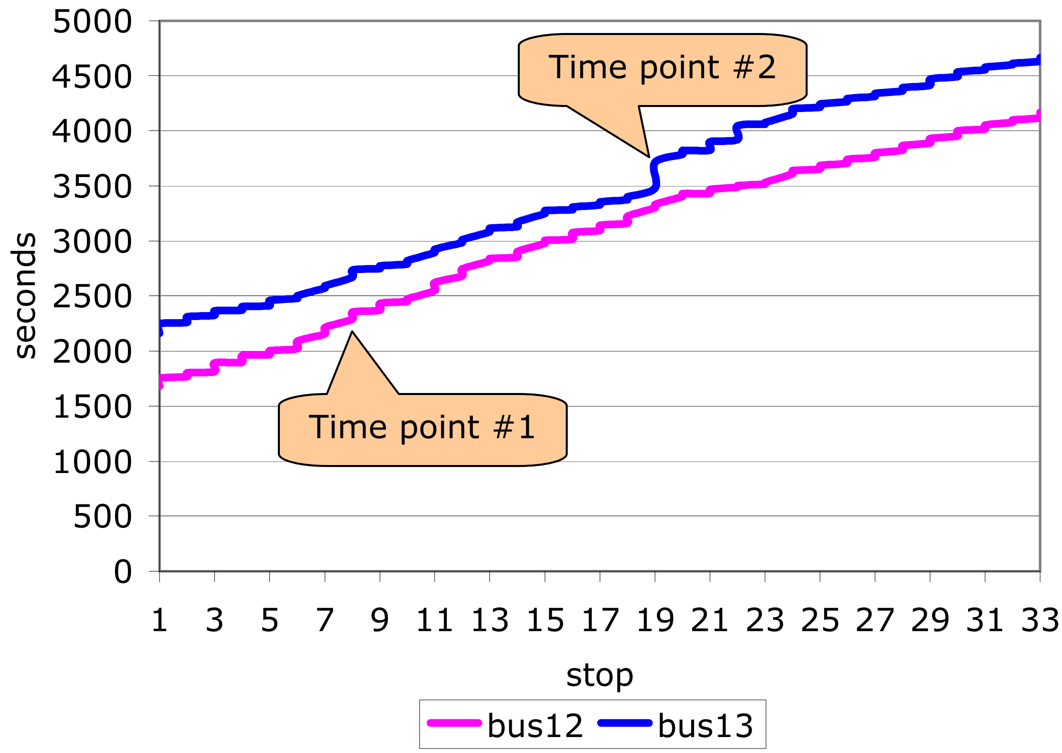

Figure 5.5: Time-space diagram of selected bus vehicles on service in outbound line 51 under headway control

In contrast, the schedule-based control strategy does not consider headway regularity, but schedule adherence. This is illustrated in Figure 5.6: The first bus in the presented subset, bus number 16, arrived ahead of schedule in both time points and therefore was held twice in order to depart as scheduled and avoid the detachment from the schedule. The following bus, bus number 1, opened a very long headway (up to twice the planned-headway), which causes the bunching of bus number 2. Since schedule adherence is the criteria on this scenario, buses 1 and 2 were hold at stop number 8, although bus 1 already opened a gap from the planned-headway. The buses are not held at stop number 19, although they had only half the planned-headway between them.

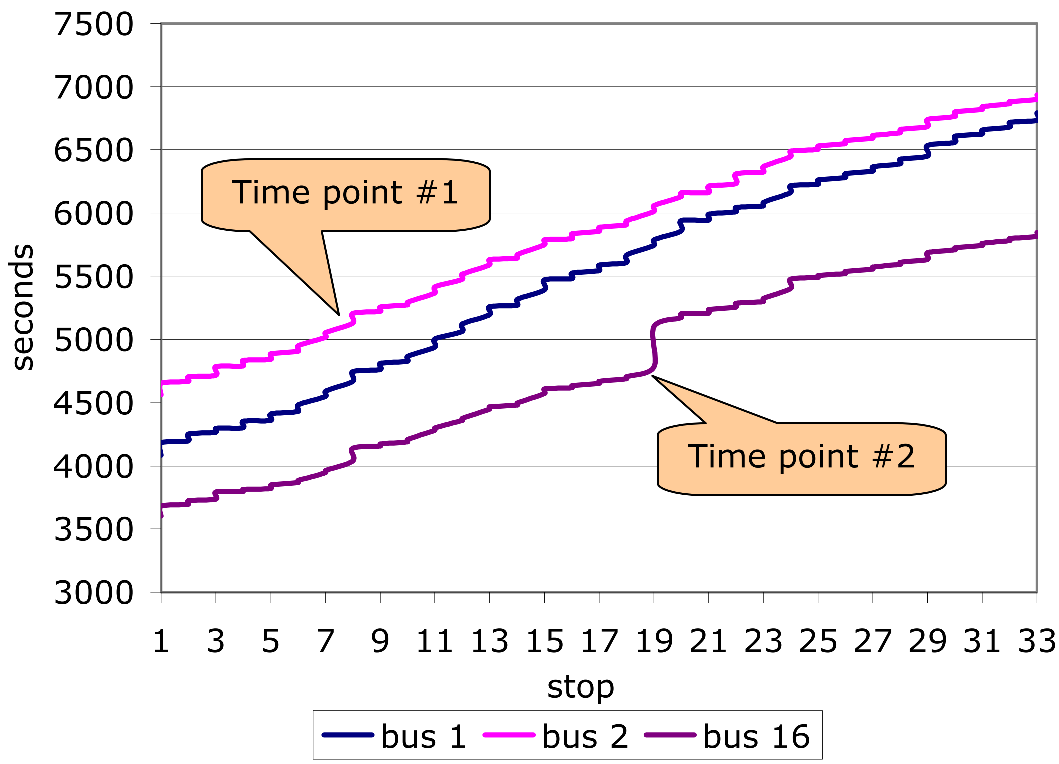

Figure 5.6: Time-space diagram of selected bus vehicles on service in outbound line 51 under schedule control

The objective of control strategies is to improve the service reliability which tends to decrease along the bus route. As Figure 5.7 clearly shows, the propagation of standard deviation of the headway along the route is restrained by the time point stops (stops 7, 13 and 21). Each time the trajectory arrived at a time point stop, the standard deviation decreased immediately and afterward continues to climb. It is important to note that the actual decrease is higher for the time points that were actually activated (according to the criteria, whether headway-based or schedule-based). As expected, the decrease is more dramatic when headway control is in place. Interestingly, the first time point, stop number 7, had no restraining effect under schedule control and only a small effect under headway control. This may be because the level of service did not reach a necessary lower threshold in order to make this time point activated and therefore effective.

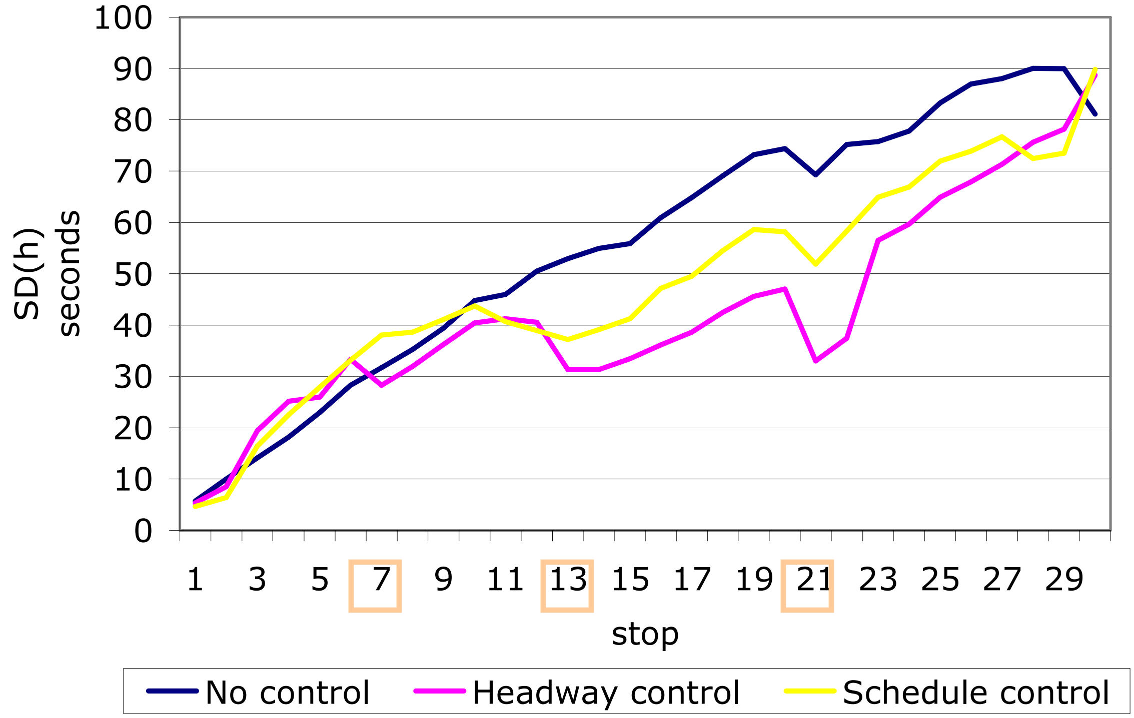

Figure 5.7: Standard deviation of headways along the inbound route (time point stops are marked with a square)

While schedule-based control is inferior to headway-based control on headway variability, when it comes to on-time performance, schedule-based control is preferable. Figure 5.8 presents the change in on-time performance measure along the bus route: the downfall in on-time performance is evident and so is the dramatic shift in time point stops (stops 8 and 19) under both control strategies. The increase under schedule control is more dramatic, but it is followed immediately by sharp decreases. An analysis of the arrival times on the stops that follow time point stops revealed that the vast majority of arrivals that failed to adhere schedule were too early (more than 60 seconds ahead of schedule). This seems to be the result of the current schedule that already contains high variability levels and results in longer gaps than necessary under control.

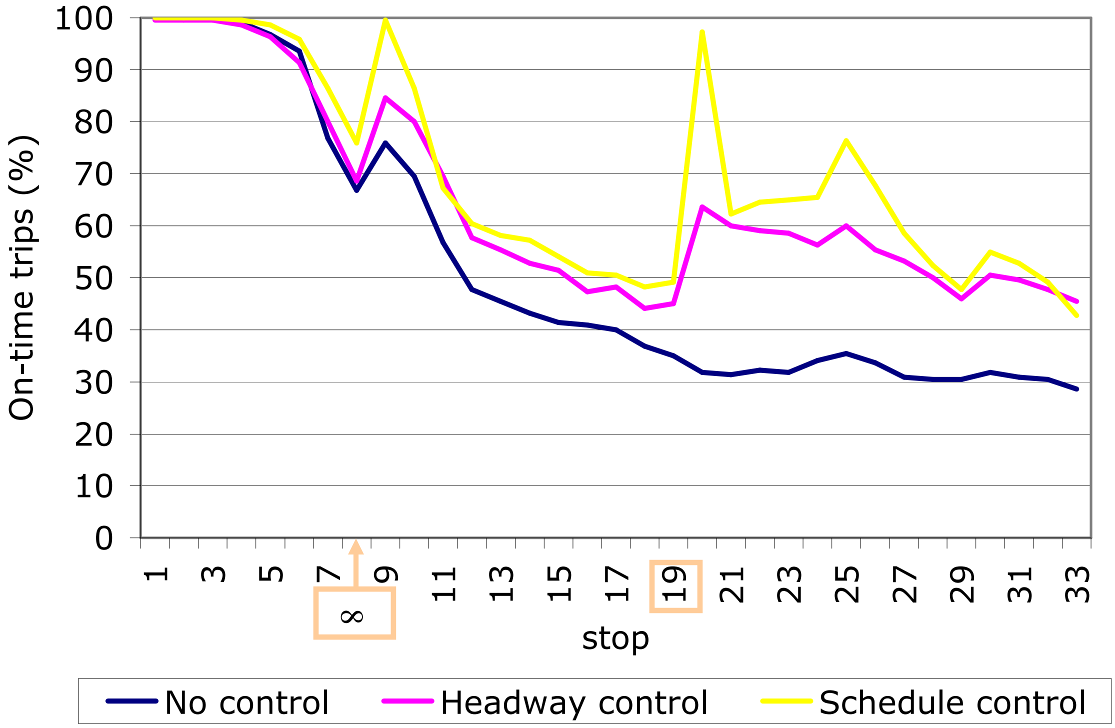

Figure 5.8: Percentage of on-time performance along the outbound route (time point stops are marked with a pink square)

5.6 Bus mechanisms' distribution

The previous sections presented aggregated means of system-level measures and the way they change along the route due to the presence of time point stops. In order to analyze and evaluate in detail the control strategies, the complete distributions of bus service components are essential. Although it involves a large data set, BusMezzo enables this approach thanks to its relatively low complexity and short run times.

The headway cumulative distribution under holding strategies is shown on Figure 5.9. The standard deviation of the headway is the lowest under headway-based control (42.52 seconds), but also schedule-based control (47.93 seconds) is lower than the no control scenario (55.67 seconds). The headway distribution under headway and schedule control is less dispersed than with no control: 20% of the headways under no control are less than half of the planned headway or more than 1.5 times the planned headway compared with only 10% under headway control or schedule control. Nonetheless, the general distribution form is similar in all cases. A slight exception to that is the large proportion of headways between 375 seconds and 395 seconds under headway-based strategy (three times more than under no control or schedule-based strategy). This is of course because the minimal headway in time point stops was set to 384 seconds (0.8 times the planned headway) and therefore all smaller headways in time point stops were truncated to this value.

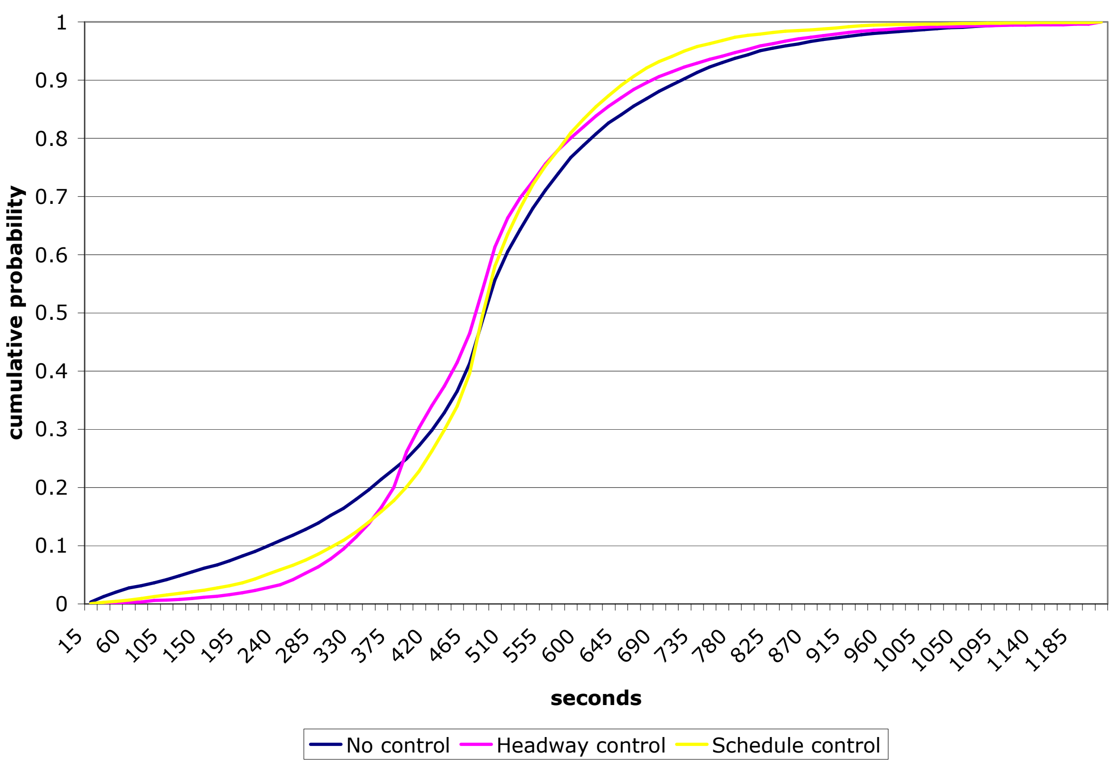

Figure 5.9: Cumulative distribution function of the headway under control strategies

The average arrival time increased from 11 seconds before schedule under no control to 33 and 43 seconds behind schedule under schedule control and headway control, respectively. The scheduled-based holding cut off the very early arrivals: only 0.7% arrived more than half a planned-headway early compared with 3.7% under headway-based control and 10.3% when no control strategy was implemented. This trend is shown on Figure 5.10, as schedule-based strategy has shorter absolute deviations from schedule than headway-based strategy, which is slightly better than no control scenario.

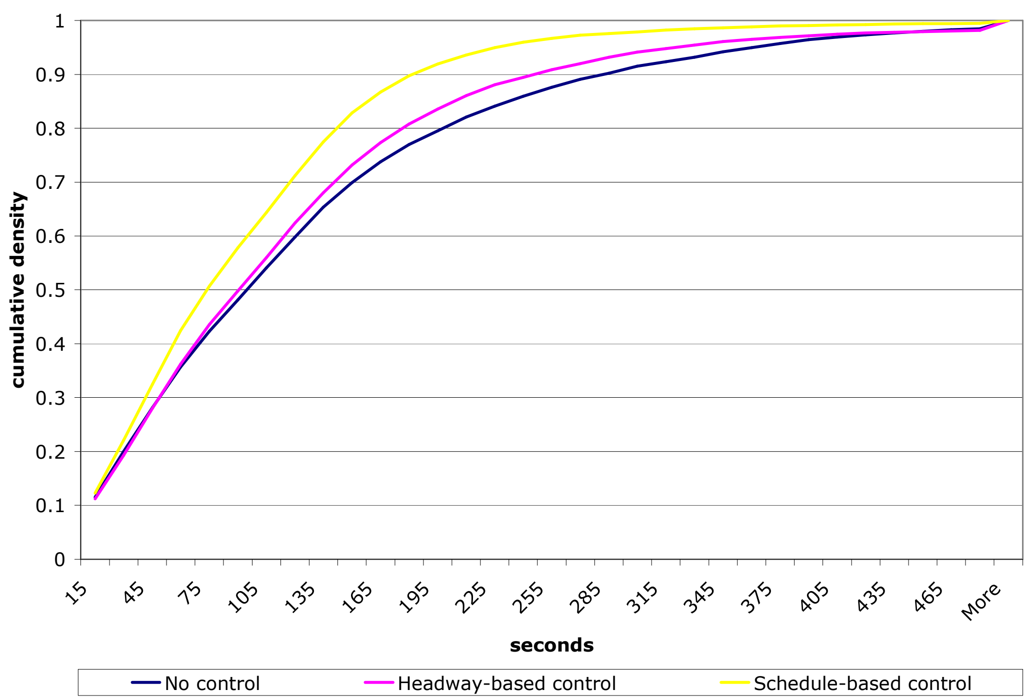

Figure 5.10: Cumulative distribution function of the absolute deviation from schedule under control strategies

5.7 Summary

The capabilities of MEZZO as an evaluation tool of transit operations and control had been demonstrated through a case study that included the implementation of holding control strategies on various scenarios. The simulation enables analysis at different aggregation levels for various scenarios in terms of demand, frequency, background traffic influence and the components of the control strategy.

The holding control was found to improve the level of service at all demand and variability levels scenarios. Headway control was most efficient in reducing the variability of headways and the bunching phenomenon, while schedule control served best the goal of improving on-time performance and minimizing the deviation from schedule. Theoretically, the objective of the selected control strategy may cause harm to other objectives. However, this was not the case in our runs – the implementation of control strategy improved system measures across the board, while only the magnitude (not the trend) is subject to the type of control strategy.

Chapter 6 : Conclusions

6.1 Summary

Computer simulations became the primary tool in recent years for evaluation and analysis of traffic planning, control and design. Simulation models follow the dynamics of the traffic system and allow the stochastic representation of complex problems. The complex, dynamic and extensive nature of public transport system calls for the development of transit simulation models. A classification of the transit simulation concluded that most of the research efforts in modelling public transport and APTS have concentrated on microscopic simulations. In addition, The few attempts to use a mesoscopic simulation that will enable large-scale applications were limited adjustments or enhancements.

Our approach was to develop a useful evaluation tool for transit operations that will enable system-wide representation and the representation of APTS applications with a modular structure. Therefore, the primary objective of this study is to develop a mesoscopic simulation model for transit operations with APTS applications. A framework for the representation and integration of the transit system components (BusMezzo) within Mezzo, a mesoscopic traffic simulation, was developed. The framework was developed in an object-oriented programming (OOP) manner.

BusMezzo represents schedules, driving rosters, boarding and alighting processes, passengers left behind, dwell time, layover and recovery time and trip chaining. It capabilities as an evaluation tool of transit operations planning and control had been demonstrated with an application to a real-world high-demand line in the Tel Aviv metropolitan area that included the implementation of real-time holding control strategies. The simulation enables analysis on different aggregation levels for various scenarios.

The main finding from the case study is that BusMezzo has the capability to reconstruct phenomenon as propagation of headway variability and the descent of on-time performance along the route, bus bunching and the relation between headway variability and demand level. The holding control was found to improve system level of service measures across the board at all demand and variability levels scenarios. Headway-based control was more efficient in improving service regularity, while schedule-based control had higher schedule adherence.

6.2 Further research

This study had tried to contribute to the body of knowledge in the transit simulation field. Many interesting aspects remained to be researched. Those aspects can be divided into two parts: model enhancements and applications.

Enhancements

The current BusMezzo simulation model can be enhanced in order to enable further applications. Passenger demand is represented in the most detailed level that represents passengers in terms of flow, without representing individual passengers. A recommended further research will introduce detailed representation of passenger demand and behaviour into BusMezzo. A passenger object will include the passenger attributes and preference to allow mode choice, including transfers. Moreover, passenger demand could be expressed in terms of

OD pair (instead of a pair of stops) to allow also the choice of bus stop.

As demonstrated in the case study, BusMezzo has the capability to simulate holding strategies, including strategies that require real-time information. Future enhancements may allow the implementation of additional APTS applications. The modelling of transit signal priority, one of the most popular APTS applications (FTA, 2000), will allow the evaluation of different priority strategies. Another interesting APTS application is skipping stops by expressing, deadheading or short-turning. Modelling of these strategies has to include a mechanism of benefit calculation, in order to consider the benefits for the passengers on-board compared with the damage for the passengers in skipped stops. Of course, both applications – signal priority and skipping - assume AVL systems and may use also data from Automatic Passenger Counters (APC).

BusMezzo allows flexibility in determining travel time variability. In case that detailed background traffic data (OD matrix) is not available or not important for the evaluated application, it is possible to generate travel times according to a lognormal distribution with given parameters. Currently, the simulation assumes independence between links' travel time. This assumption is not realistic, since traffic conditions, and therefore link travel times, are affected by adjacent links. A further research can implement dependence between link travel times under various traffic conditions and link connections.

Applications

The case study that was presented in Chapters 5 and 6 was based on a real-world data on a high demand bus line and included the implementation of holding control strategies. The simulation is yet to be tested on a realistic system-wide network as a metropolitan system. In addition, a validation research can compare the evaluation of holding strategies by the simulation to field data on control consequences.

Regarding holding control strategies, it is assumed that schedule-based holding and headway-based holding suits different frequencies (e.g. Abkowitz and Engelstein, 1984). Intuitively, headway-based holding suits best short and uniform headways, while a service with long and irregular headways would benefit more from a schedule-based holding. This assumption can be tested by simulating various frequency scenarios in order to find the threshold frequency. It should be noted that the number of boarding passengers should be adjusted for long headways service, when passengers tend to time their arrival according to the schedule.

The calibration of transit mechanisms is one of the research interests for the public transport authority to be established in the Tel-Aviv metropolitan. BusMezzo simulation can be applied as a calibration tool for transit mechanisms as dwell time, running time and recovery time parameters. The calibration may compare simulated values to AVL and APC field data, which is widely available.

Finally, the various components of the holding control strategies can be tested by using BusMezzo simulation. The number of time point stops, their location and the size of the minimal headway or slack size are possible subjects for future applications. Although all of the reviewed studies in the field (Section 6.2) assumed that the holding expression equals the holding criterion, there is no theoretical constraint for this identity. For example, one might suggest that the holding criterion for headway-based control would be separated from the value of the minimal headway.

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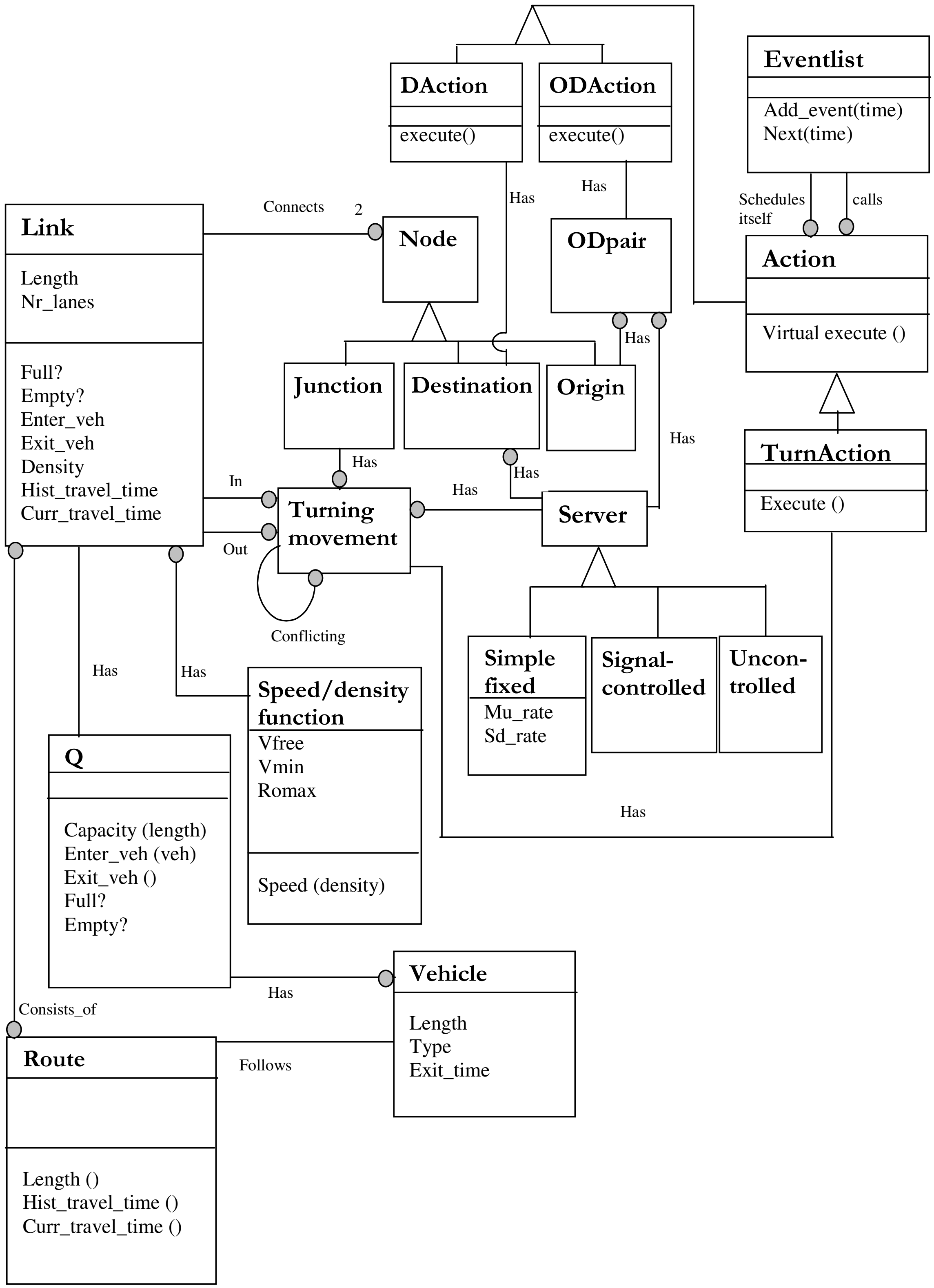
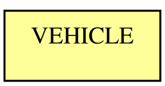
Appendix A - Mezzo Object Model (simplified)



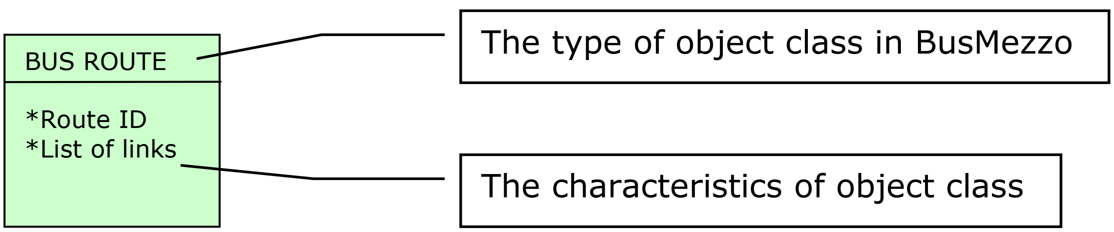
Appendix B – Object model notations

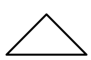
This object model shows the general structure of the classes in BusMezzo. This graphical presentation is part of the Unified Modelling Language (UML), which is a common standard in computer science (Burghout, 2004).

The following legend should be used for UML Object Models:

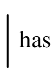


Object Class in general MEZZO

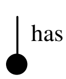




Subclass (i.e. a BUS VEHICLE is a *subclass* of a VEHICLE)



1 to 1 relationship between Object Classes (a BUS LINE has 1 BUS ROUTE)



1 to Many relationship between Object Classes (a BUS LINE has many BUS TRIPs)

Appendix C - Classes relations

BusMezzo object classes are completely integrated into Mezzo. Each class object has a network of interactions with other related objects. There are two types of class relations:

(1) Inheritance – The object type that inherits, shares all the characteristics of the object that is been inherited. In addition, it includes definitions of additional unique characteristics and functions.

(2) Reference – Objects are related to each other by pointers or function calls.

Each object in BusMezzo has relations with several other objects. 'Doxygen', free software available on the net, documents C++ programs and generates relations diagrams. Figures B.1-B.3 presents the class reference for BUSROUTE, BUS and BUSLINE, respectively. The diagram includes all direct inheritance and references relations. In order to be informative and convenient at the same time, some remote relations may be omitted, as marked by red frame.

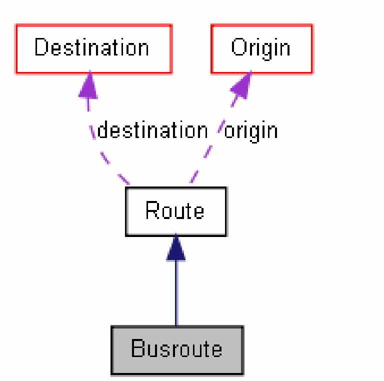


Figure C.1: BUSROUTE class relations

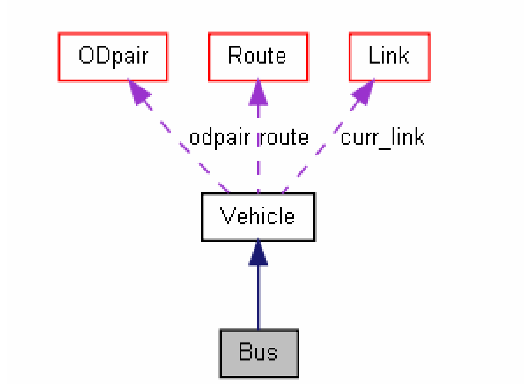


Figure C.2: BUS class relations

BUSROUTE, BUS and BUSLINE inherit from general objects in Mezzo, ROUTE, VEHICLE and ACTION, respectively. Each of the prototypes refers to few fundamental characteristic: fixed - as ORIGIN in the case of ROUTE, or VTYPE (which stands for vehicle types) for BUSLINE, or dynamic - as LINK in the case of BUS or ODpair for BUSLINE.

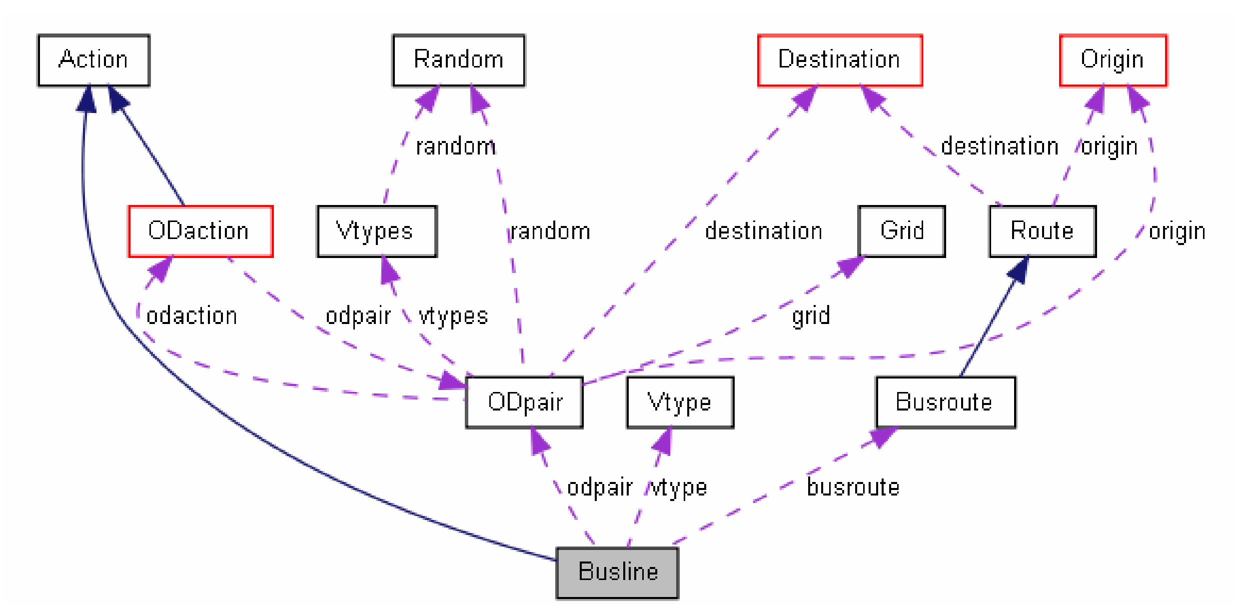


Figure C.3: BUSLINE class relations

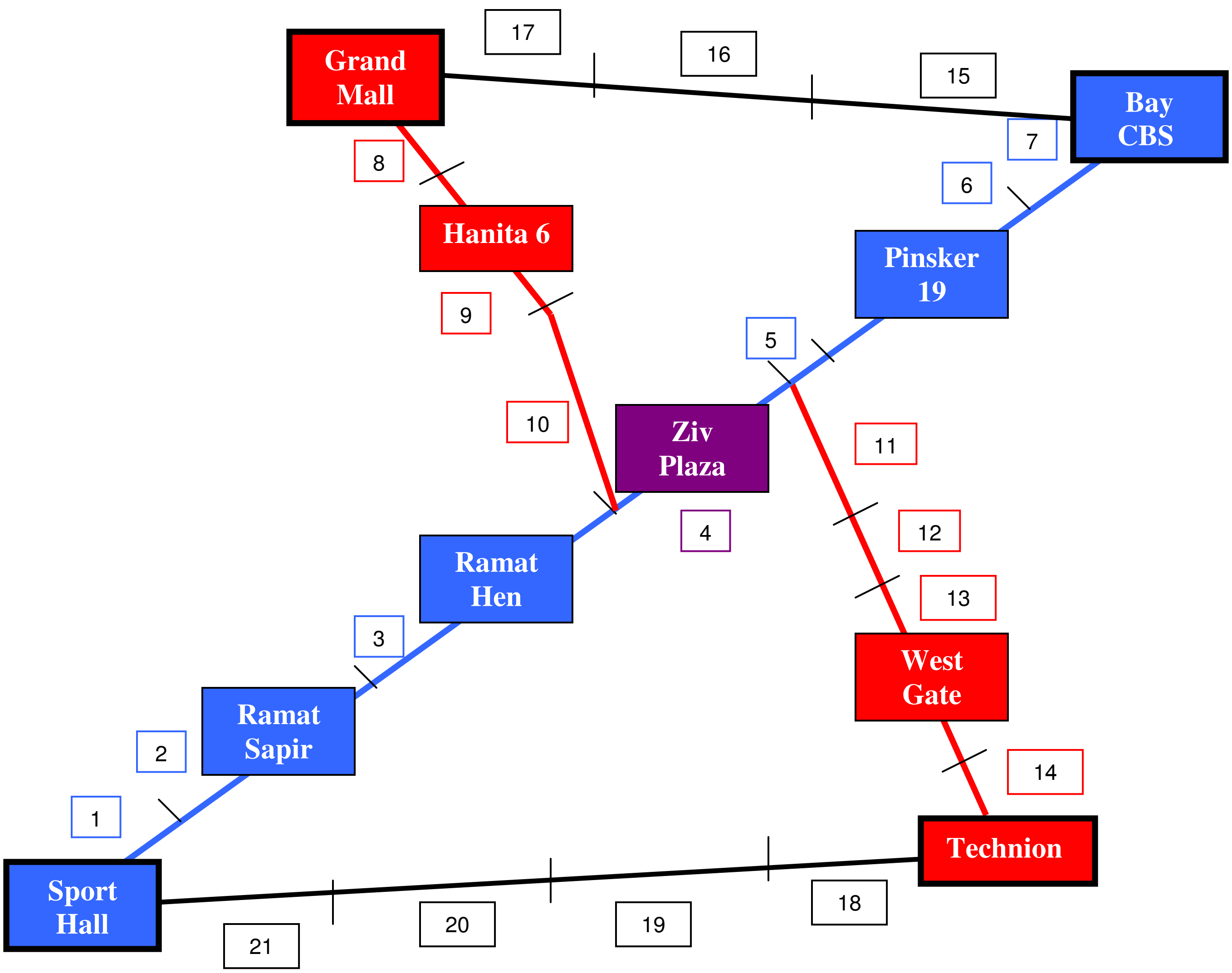
Legend:

Busroute	The class for which the graph is generated
Route	A related class
Busline	A related class for which not all relations are shown
→	Inheritance relations
- - →	Reference relations, when the class is contained by another class. The arrow is labelled with the variable through which the pointed class is accessible.

Appendix D – Input Format

The transit network is defined by six additional input sections: bus stops, bus lines, bus routes, bus trips, bus vehicles and passenger demand. The input format was designed in the same manner as the existing MEZZO input files.

The following example network is used to demonstrate the transit-related input files. The network includes two service lines: the red line with 5 stops and the blue lines with 6 stops. One stop, "Ziv Plaza", functions as a transfer stop. In addition, there are two deadheading routes, presented in black.



Legend:

Technion	Bus terminal
Ramat Sapir	Bus stop
	Bus route
1	Link number

The published schedule between 8:00 a.m. and 9:00 a.m. is as follows:

Line 1 ("South Cross")					
Sport Hall	Ramat Sapir	Ramat Hen	Ziv Plaza	Pinsker 19	Bay C.B.S
8:00	8:02	8:06	8:11	8:15	8:20
8:15	8:17	8:21	8:26	8:30	8:35
8:30	8:32	8:36	8:41	8:45	8:50
8:45	8:47	8:51	8:56	9:00	9:05

Line 2 ("Newe Shaanan")				
Grand Mall	Hanita 6	Ziv Plaza	West Gate	Technion
8:00	8:02	8:08	8:11	8:15
8:30	8:32	8:38	8:41	8:45

D.1. Bus stops

This section defined the physical characteristics of each bus stop. The definition of bus stops has the following form:

{ Stop_ID Stop_Name Link_ID Position Length
Type Minimal_dwell_time }

Where:

Stop_ID	A unique identification number	integer
Link_ID	The identification number of the link on which the stop is located	integer
Position	The position of the stop, as distance in meters from the upstream node	double
Length	The available space in the stop, in meters	double
Type	0 for in-lane stop and 1 for bay stop	binary
Minimal_dwell_time	Constant minimal possible dwell time per stop	double

Example:

```
Busstops:  10
{   1    Sport_Hall    1    0.0      16.0  1   5,0   }
{   2    Ramat_Sapir   2    28.7     12.0  0   0.0   }
{   3    Ramat_Hen     3    115.0    12.0  0   0.0   }
{   4    Ziv_Plaza     4    82.5     24.0  1   5.0   }
{   5    Pinsker_19    6    34.2     12.0  0   0.0   }
{   6    Bay_CBS       7    345.0    36.0  1   10.0  }
{   7    Grand_Mall    8    0.0      15.0  1   5.0   }
{   8    Hanita_6      9    187.6    12.0  0   0.0   }
{   9    West_Gate     13   256.3    9.0   1   0.0   }
{   10   Technion      14   321.3    18.0  1   10.0  }
```

D.2. Bus lines

The line is defined by OD pair, reference to the route in terms of links, a sequence of bus stops and a sub-set of time point stops. The definition of bus lines has the following form:

```
{   Line_ID    Line_Name          Origin_ID   Destination_ID
    Route_ID   Vehicle_Type_ID    Number_of_Stops      {
    Stop_ID1   Stop_ID2    …      }     }
    Number_of_Time_Points         {     Time_Point_ID1
    Time_PointID2    …     }
}
```

Where:

Line_ID	A unique identification number	integer
Line_Name	A descriptive name	string
Origin_ID	The ID of the origin node	integer
Destination_ID	The ID of the destination node	integer
Route_ID	The ID of the bus route	integer
Vehicle_Type_ID	The ID of the required bus vehicle type	integer

Example:

```
Buslines:   4
{   1   South_Cross      1   2   1   1   6   {   1
    2   3   4   5        6   }   1   {   4   }
}
{   2   Newe_Shaanan     3   4   2   1   5   {   7
    8   4   9   10       }   1   {   4   }
}
{   3   Deadheading_23   2   3   3   1   0   {   }
}
{   4   Deadheading_41   4   1   4   1   0   {   } }
```

D.3. Bus routes

The definition of bus routes, in terms of links, has the following form:

```
{    Route_ID    Origin_ID    Destination_ID    Number_of_Links
     {    Link_ID1    Link_ID2    …    }
}
```

Example:

```
Busroutes: 4
{    1    1    2    7
     {    1    2    3    4    5    6    7    }
}
{    2    3    4    8
     {    8    9    10    4    11    12    13    14    }
}
{    3    2    3    3
     {    15    16    17    }
}
{    4    4    1    4
     {    18    19    20    21    }
}
```

D.4. Bus trips

Bus trip, also known as bus run, storages the schedule information. The definition of bus trips has the following form:

```
{    Trip_ID    Line_ID    Dispatch_Time    Number_of_Stops
     {    Stop_ID1    Departure_Time    }
     {    Stop_ID2    Departure_Time    }
     {    …           …                 }
}
```

Where:

Trip_ID	A unique identification number	integer
Dispatch_Time	Dispatching time from origin terminal as appears in the schedule, in seconds from the beginning of the simulation	double
Departure_Time	Departure time from bus stop as appears in the schedule/operator, in seconds from the beginning of the simulation	double

Example:

```
Bustrips: 8
{	1	1	0.0		6
	{	1	0.0		}
	{	2	120.0		}
	{	3	360.0		}
	{	4	660.0		}
	{	5	900.0		}
	{	6	1200.0		}
}
{	2	1	900.0		6
	{	1	900.0		}
	{	2	1020.0		}
	{	3	1260.0		}
	{	4	1560.0		}
	{	5	1800.0		}
	{	6	2100.0		}
}
{	3	1	1800.0		6
	{	1	1800.0		}
```

```
	{	2	1920.0	}
	{	3	2160.0	}
	{	4	2460.0	}
	{	5	2700.0	}
	{	6	3000.0	}
}
{	4	1	2700.0	6
	{	1	2700.0	}
	{	2	2820.0	}
	{	3	3060.0	}
	{	4	3360.0	}
	{	5	3600.0	}
	{	6	3900.0	}
}
{	5	2	0.0	5
	{	1	0.0	}
	{	2	120.0	}
	{	3	480.0	}
	{	4	660.0	}
	{	5	900.0	}
}
{	6	2	1800.0	5
	{	1	1800.0	}
	{	2	1920.0	}
	{	3	2280.0	}
	{	4	2460.0	}
	{	5	2700.0	}
}
{	7	3	1200.0	0
```

```
}
{     8     4     900.0     0
}
```

D.5. Passenger demand

Demand data includes the demand to board and alight in each bus stop for every bus line. The definition of passenger demand has the following form:

```
{     Stop_ID     Line_ID     Arrival_Rate     Alighting_Fraction
      }
```

Where:

Arrival_Rate	The expected value of the number of passengers that arrive in an hour	integer
Alighting_Fraction	The probability that a passenger on-board will alight	double, between 0 and 1

Example:

Passenger_rates: 11

```
{     1     1     50     0.0     }
{     2     1     20     0.2     }
{     3     1     16     0.1     }
{     4     1     64     0.5     }
{     4     2     34     0.6     }
{     5     1     20     0.2     }
{     6     1     0      1.0     }
{     7     1     24     0.0     }
{     8     1     15     0.3     }
```

```
{    9    1    10    0.15 }
{    10   1    0     1.0  }
```

D.6. Bus types

This section defined the physical characteristics of each bus type. The definition of bus types has the following form:

```
{    Bus_Type_ID    Bus_Type_Name        Length
     Number_of_Seats      Capacity    }
```

Where:

Bus_Type_Name	A descriptive name	string
Capacity	Maximum possible occupancy: sitting and standing	integer

Example:

```
Bustypes: 1
{    1    Urban          12.0     38    62    }
```

D.7. Bus vehicles

Bus vehicle storages the driving roster information. The definition of bus vehicles has the following form:

```
{    Bus_Vehicle_ID  Bus_Type_ID    Number_of_Trips
     {    Trip_ID1   Trip_ID2   …    }
}
```

Where:

Bus_Vehicle_ID	a unique identification number	integer

Example:

```
Busvehicles: 4
{    1    2    3
     {    1    7    6    }
}
{    2    2    3
     {    5    8    3    }
}
{    3    2    1
     {    2    }
}
{    4    1    1
     {    4    }
}
```

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המכון לחקר התחבורה

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מאת

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הבעות תודה

עבודה זו היא תוצר של מאמץ בן שנתיים שלא יכול היה להגיע לכדי מיצוי ללא התמיכה וההדרכה של הבאים:

התמיכה הכספית הנדיבה של הטכניון אשר הייתה חיונית על מנת להקדיש את זמני לעבודת התזה.

המחקר נעשה בהנחיית ד״ר תומר טולדו בפקולטה להנדסה אזרחית וסביבתית ביחידה להנדסת תחבורה וגיאו-אינפורמציה. אופן הדרכתו, עצותיו ועידודו מוערכים עד מאוד. פגישותינו תמיד סיפקו לי תובנות רבות ערך לגבי המשך ההתקדמות בעבודה ואופן עריכת מחקר. השראתך תרמה רבות למשיכתי לתחום המחקר.
ד״ר ווילקו בורחהאוט אפשר לי להתמודד עם האתגר הכרוך בתכנות שנדרש לעבודה זו. בסבלנות אין קץ ובמצב רוח טוב, הוא הדריך אותי בנבכי התכנות נוחה העצמים. בנוסף, שיחותינו וביקורי במכון הטכנולוגי המלכותי של שטוקהולם סייעו בהתמודדות עם סוגיות תכנות ומודלים של סימולציה.
תודה לפרופ׳ חריס קאוטסופולוס עבור עצותיו והעניין שהפגין לאורך העבודה. תבונותיו תרמו רבות לייצוג התפעול של תחבורה ציבורית ולתכנון מקרה הבוחן.
ד״ר שלמה בכור, עבור הנתונים שסיפק לצורך מקרה הבוחן והעניין והדאגה המתמשכים שלו.
ברצוני גם להודות לעמיתי מהיחידה לתחבורה ולמזכירות מסבירות הפנים.
אני אסיר תודה לתמיכה והאהבה של משפחתי. במיוחד, להוריי על אמונתם המתמדת בי ולכך שתמיד עודדו אותי ללכת בעקבות סקרנותי.
אחרון חביב, אהובי. על כך שחלקת איתי את רגעי התסכול והסיפוק בהומור ואהבה. בזכות חברתך, עוז, המסע הזה היה נעים.

תקציר

בשנים האחרונות קיים עניין גובר בניצול יעיל יותר של תשתיות התחבורה ובמדיניות ניהול ביקושים בכלל, ובתחום התחבורה הציבורית, בפרט. פיתוח מערכות התחבורה הציבורית בעולם מתבטא בריבוי אמצעים, הסדרי העדפה ושילוב מערכות תחבורה ציבורית המבוססות על טכנולוגיות מתקדמות (APTS). כפועל יוצא, נדרשים כלים חדשים לתכנון, תפעול והערכה של מערכות אלו. כלים אנליטיים אינם מהווים פתרון מספק עקב ההיקף והמורכבות, כמו גם אופיין הדינאמי של מערכות התחבורה הציבורית.

מודלים של סימולציה מהווים כלי מרכזי בתכנון ובקרת תנועה ובהערכת מערכות תחבורה מתקדמות (ITS). סימולציות תנועה הן בעלות פוטנציאל רב לשמש ככלי תכנון וניתוח מערכות תחבורה ציבורית, בשל ישימותן, גמישותן, יכולתן לייצג תהליכים מתמשכים דינאמיים ויחסי גומלין בין רכיבי מערכת והאפשרות להשוות בין תרחישים שונים. אף על פי כן, לא נעשו מאמצים רבים לפיתוח מודלים לסימולציה של תחבורה ציבורית. מודלים של סימולציות תנועה מסווגים לפי רמת האגרגטיביות: מאקרוסקופים- התקדמות התנועה מחושבת לפי פונקציות זרימה, ללא ייצוג מפורש של כלי רכב בודדים ונתיבים; מיקרוסקופים- ייצוג מפורט של כלי רכב בודדים, יחסי גומלין בין כלי רכב, גיאומטריה, הקצאת נתיבים וכדומה; מזוסקופים – ייצוג רכבים בודדים, אך ללא ייצוג מפורט של תנועתם. ייצוג מערכות תחבורה ציבורית דורש מחד גיסא ייצוג מפורט של רכיבי מערכת ומאידך גיסא נדרשת יכולת לייצג רשת בסדר גודל של מטרופולין, על מנת להעריך את ביצועי התחבורה הציבורית ברמה המערכתית. לפיכך, מודל של סימולציית תנועה מזוסקופית הוא המתאים ביותר לשמש כפלטפורמה לסימולציה של תחבורה ציבורית.

סקירת מחקרים שעסקו במודלים של סימולציית תחבורה ציבורית הצביעה על כך שניתן להבחין בין שלוש רמות אינטגרציה בייצוג תחבורה ציבורית במסגרת סימולציית תנועה:

1. התאמות– שימוש במודלים של סימולציה שאינה מייצגת תחבורה ציבורית באמצעות ביצוע התאמות או מניפולציות חיצוניות למודל. העדר ייצוג מפורש

לרכיבי מערכת התחבורה הציבורית מגביל מאוד את טווח היישומים ורמת הדיוק בגישה זו.

2. הרחבות– הוספה נקודתית או חלקית של מאפייני תחבורה ציבורית למודלים של סימולציה שאינה מייצגת מפורשות תפעול תחבורה ציבורית או שמייצגת תחבורה ציבורית באופן בסיסי בלבד. ההרחבות מבוצעות לרוב על ידי תכנות חיצוני לתוכנת הסימולציה הבסיסית. מחקרים רבים שהתמקדו בהיבטים ספציפיים בתפעול תחבורה ציבורית נקטו בגישה זו בשל חסכנותה. חסרונה של שיטה זו בגישתה הפשטנית להיבטי תפעול תחבורה ציבורית אשר מחוץ למוקד המחקר.
3. פיתוח- מודלים של סימולציה שפותחו באופן ייעודי לייצוג מאפייני תפעול תחבורה ציבורית או שייצוג תחבורה ציבורית הוטמע לחלוטין בתוך מודל הסימולציה. מחקרים בודדים בלבד פיתחו מודל מיקרוסקופי כוללני לסימולציית תחבורה ציבורית המאפשר ייצוג מפורט של מאפייני תפעול תחבורה ציבורית ברמה הנקודתית. למיטב ידיעתנו, לא פותח מודל סימולציה מזוסקופית לתפעול תחבורה ציבורית המאפשר ניתוח ויישום ברמת מערכת.

הפיתוח של מודל סימולציה מזוסקופית להערכה ותכנון של מאפייני תפעול תחבורה ציבורית נעשה על גבי הפלטפורמה של מזו (Mezzo), מודל סימולציית תנועה מזוסקופית. קטעי דרך במזו כוללים שני חלקים: קטע דרך בתנועה עבור כלי רכב אשר אינם מעוכבים כתוצאה מאילוצי קיבולת היציאה וקטע דרך בתור אשר מתחיל בקודקוד הסיום של קטע הדרך ונמשך במעלה הקטע כאשר קיימת חריגה ממגבלת קיבולת היציאה. החלוקה בין קטע הדרך בתנועה וקטע הדרך בתור היא דינמית ומשתנה בהתאם לגודש התנועה. לכל נתיב פנייה קיים שרת סטוכסטי בלתי תלוי אשר מנהל את התור בהתאם לקיבולת הפנייה. כלי הרכב מיוצרים בסימולציית מזו בהתאם למטריצת מוצא-יעד בתהליך פאוסוני. בחירת מסלולים נעשית באמצעות מודל לוג'יט מולטינומי, הן טרם הנסיעה והן במהלך הנסיעה. התוכנה כתובה באופן מודולארי בשיטת תכנות מונחה עצמים (OOP) בשפת C++.

מודל סימולצית מזו לתחבורה ציבורית (BusMezzo) פותח במסגרת סימולצית מזו ומוטמע בתוכה לחלוטין. המודל כולל שישה אובייקטים לייצוג תחבורה ציבורית: סוג

הרכב, כלי הרכב, קו שירות, נסיעה, מסלול ותחנה. מודל הסימולציה כולל את מאפייני כל אובייקט, האופן בו הוא מקושר לאובייקטים הקיימים במזו וליתר האובייקטים של תחבורה ציבורית. בתחילת הסימולציה, כל האובייקטים מאותחלים לפי הקלט ולאחר מכן ההתקדמות בסימולציית מזו מבוססת אירועים – הסימולציה מתקדמת באמצעות מעבר מאירוע לאירוע המסודרים ברשימת אירועים כרונולוגית. לכן, תכנון מודל הסימולציה כלל הגדרת ההתרחשויות ברשת אשר יהוו אירועי תחבורה ציבורית, למשל: כניסה לתחנת אוטובוס, יצירת אוטובוס ויציאה מקטע נסיעה. במהלך ריצת הסימולציה, מזו מזהה באמצעות שאילתות התרחשויות ברשת שהוגדרו כאירועים ומעדכנת את רשימת האירועים. עם שליפת האירוע מהרשימה, מבוצעות פעולות מתאימות, נבדק הצורך בהזמנת אירוע עוקב ובהפקת רשומת פלט. בנוסף, תהליך הסימולציה כולל קבלת החלטות בקרה ושליטה. בכל פעם שהסימולציה שולפת אירוע מתבצעות שתי שאילתות עוקבות: האם האירוע הוגדר על ידי המשתמש כבעל פוטנציאל בקרה ושליטה; אם כן-מהי הפעולה המתבקשת לפי הקריטריונים שהוגדרו.

כל כלי לתכנון וניתוח כולל הנחות על מאפייני התפעול המרכזיים של תחבורה ציבורית: התנהגות נוסעים, זמני עיכוב בתחנות, זמני נסיעה ושרשור נסיעות. הביקוש מיוצג באמצעות מספר הנוסעים המגיעים לכל תחנה עבור כל קו וההסתברות של נוסע לרדת מכל קו בכל תחנה. זוהי הייצוג המפורט ביותר אשר איננו דורש ישויות של נוסעים בודדים. הסימולציה כוללת תהליך פאוסוני להגעת נוסעים לתחנות ותהליך בינומי להורדת נוסעים בתחנות. בנוסף, תהליך העלאת הנוסעים מוגבל על ידי התפוסה באוטובוס ומתחשב בנוסעים שנשארו מאחור. מספר הנוסעים העולים והיורדים משפיע גם על זמן העיכוב בתחנה הנקבע על ידי עיכוב קבוע והדלת עם זמן השירות הארוך ביותר. משך העיכוב תלוי גם בצפיפות על האוטובוס, סוג התחנה, מקום פנוי בתחנה ופיזור הנוסעים בין הדלתות. זמן הנסיעה בין תחנות תלוי בתנאי התנועה, בדומה לכל כלי רכב המיוצג במזו. בנוסף, קיימת אפשרות להגריל את זמני הנסיעה מתוך התפלגות נבחרת. אפשרות חסכונית זו מיועדת למקרים בהם חסרים נתוני תנועת רקע או כאשר מעוניינים לבחון השפעת שינויים בזמני הנסיעה או באמינותם. אמינות השירות תלויה גם בזמן ההגעה לתחנת הקצה אשר עלול לגרום לאיחור ביציאה לנסיעה המשורשרת. לצורך כך, מפעילי התחבורה הציבורית מקצים זמן מנוחה ומרווח בטחון בין נסיעות המיוצגים במודל הסימולציה של מזו.

היכולות של סימולציית מזו לתחבורה ציבורית נבחנו באמצעות הדגמה עם נתוני אמת אודות קו 51 של חברת דן בין תל אביב לפתח תקווה. ההדגמה כללה תשעה תרחישים עם שלוש רמות ביקוש ושלוש רמות שונות בזמני הנסיעה. הקלט הנדרש כולל את מסלולי הקו במונחי קטעים ותחנות, לוח זמנים ושיבוץ נסיעות, מטריצת ביקושים ומאפייני אוטובוסים ותחנות. ההדגמה נועדה לבחון את הייצוג של מאפייני התפעול של תחבורה ציבורית ולהדגים את הפלט המתקבל. מדדי השירות כוללים בין השאר תפוסה, זמני עיכוב בתחנות, זמן המתנה לנוסע ממוצע, מרווח בין מופעים וסטייה מלוח הזמנים. הסימולציה מאפשרת הפקת מדדי ביצוע ושירות החל ברמת הנסיעה הבודדת, עבור ברמת הקו, התחנה או הרכב וכלה ברמת כלל המערכת. ההדגמה המחישה את יכולתה של מזו לשחזר תופעות ידועות: עלייה מתמדת בשונות המרווח בין מופעים והירידה התלולה בעמידה בלוח זמנים לאורך המסלול, הצמדות אוטובוסים עוקבים והקשר בין רמת הביקוש ושונות המרווח.

הדגמת היכולות של סימולציית מזו לתחבורה ציבורית הורחבה לבחינת יישום אסטרטגיות בקרה ושליטה בזמן-אמת שמטרתן לשפר את אמינות השירות ותפעול מערכת התחבורה הציבורית. מקרה הבוחן כלל שתי אסטרטגיות להחזקת אוטובוס בתחנה: אסטרטגיה מבוססת לוח זמנים ואסטרטגיה מבוססת מרווחים בין מופעים. מספרן ומיקומן של תחנות בעלות פוטנציאל החזקה, כמו גם המרווח המינימאלי והחריגה המינימאלית מהלוח זמנים, נקבעו על פי השיטות המקובלות בתחום. מקרה הבוחן כלל תשעה תרחישים, בדומה להדגמה. אסטרטגיות ההחזקה שיפרו את רמת השירות מעבר לכל רמות הביקוש והשונות בזמני הנסיעה. בעוד אסטרטגיית החזקה מבוססת לוח זמנים הייתה עדיפה בשיפור העמידה בלוח זמנים וצמצום הסטייה מהלוח זמנים, אסטרטגיית החזקה מבוססת מרווחים בין מופעים הייתה אפקטיבית יותר בהפחתת שונות המרווחים וצמצום תופעת ההצמדות של אוטובוסים עוקבים.

ישנם עוד היבטים רבים בהם ניתן להעשיר או לבחון באמצעות יישום במודל הסימולציה של מזו לתפעול תחבורה ציבורית. כיווני מחקר עתידיים מעניינים כוללים ייצוג מפורט של נוסעים על מאפייניהם והעדפותיהם והרחבת היישומים של מערכות תחבורה ציבורית מתקדמות, דוגמת העדפה ברמזורים או דילוג על תחנות. כמו כן, יש צורך לבחון את הסימולציה על רשת מציאותית בסדר גודל של מטרופולין. בהקשר של

אסטרטגיות החזקה, ניתן לבדוק מידת התאמתן לתדירויות שונות והשינוי באפקטיביות שלהן כתוצאה משינוי פרמטרים דוגמת מספר תחנות ההחזקה, מיקומן וקריטריון ההחזקה.