The Development of More Effective Operating Plans for Bus Service

by

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Abstract

This thesis develops relationships between schedule parameters, operational cost, and service quality involved in the scheduling process, which will help a decision-maker to choose the schedule that best fits his or her objectives. It also proposes a scheduling process, which incorporates the developed relationships and enables schedulers to explore different combinations of schedule parameters. The developed relationships are demonstrated and the proposed scheduling process is applied in a case study of the Chicago Transit Authority bus route 77.

The trip time distribution changes depending on the headway and the schedule time since the headway and schedule time affects the dwell time and movement time respectively which are components of the vehicle trip time. The half cycle time and recovery time are determined by the desired on-time departure probability at the terminal and the trip time distribution that is determined by the schedule time and headway. Therefore, any changes in the headway and schedule time will influence decisions on other schedule parameters.

The operational cost includes both the schedule cost and cost of any late trip. The schedule cost during a time period is determined by the cycle time and headway and the late trip cost is determined by the trip time distribution and cycle time. The service quality is measured by the in-vehicle time, crowding level, passenger waiting time, and schedule adherence. The in-vehicle time is affected by the headway and schedule time, the waiting time and crowding level are affected by vehicle headway and recovery time, and the schedule adherence is affected by the schedule time and recovery time.

The case study showed that understanding and applying those relationships to the proposed scheduling process can help transit agencies develop more effective operations plans by recognizing the tradeoffs between the schedule parameters, operational cost and service quality. The recommended schedule parameters under the current headway resulting from the proposed scheduling process could significantly reduce operational costs while improving the passenger waiting time and on time arrival probability compared to the current schedule.

Thesis Supervisor: Nigel H.M. Wilson
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Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

This thesis develops relationships between schedule parameters, operational cost, and service quality involved in the scheduling process. The developed relationships are demonstrated through application to a specific bus route. The application shows that understanding and applying those relationships to the scheduling process can help transit agencies develop more effective operations plans.

1.1. Motivation

Maintaining transit service reliability has long been a major concern of both transit operators and users. Failure to maintain transit service reliability results in late departures, bunching, crowding and missed trips. Transit operators will have to bear higher operating costs and purchase additional vehicles to solve these problems. Unreliable service increases passenger wait times and levels of crowding, and thus discourages potential customers from using transit. This translates into lost revenue as well as ridership for the transit agencies. Thus, transit operators have long been interested in finding means to improve service reliability. Research on improving service reliability on bus routes is especially important since bus routes are vulnerable to traffic congestion because buses share the road with other traffic unlike trains, which usually have their own right of way.

Fortunately, with the development over the past two decades of Intelligent Transportation System (ITS), Automatic Vehicle Location (AVL) and Automatic Fare Collection (AFC) systems more detailed information can be obtained on running times and passenger demand than with traditional manual data collection. This enables faster and more accurate data analysis and service performance evaluation under the current timetable, and therefore more rapid adjustment of the timetable. However, in reality, most transit providers cannot readily utilize the data gained from existing AVL and AFC systems for off-line analysis and in the scheduling process even if they have made large investments in AVL systems. Therefore, research is needed to utilize those data more efficiently in the scheduling process and to estimate the benefit of more accurate information on running time and passenger demand in terms of developing more effective timetables.

Developing a timetable involves different objectives. Passengers are interested in minimizing their waiting time and riding time, and thus prefer short scheduled running time, high frequency and high reliability. They are also concerned about crowding levels, which again makes them prefer high frequency and high reliability. The operator is interested in minimizing operating costs, and thus prefers short running time, minimum frequency and minimum recovery time (although they want recovery time to be sufficient that most return trips can begin on time). However, high reliability and short scheduled running times are in conflict since the probability that a driver stays on schedule decreases as the schedule becomes tighter (i.e. the schedule running time become shorter). Therefore, service reliability deteriorates. In addition, the optimal schedule for the passengers is not necessarily optimal for the operator. Thus, a transit operator should make decisions on the tradeoffs between operating costs and passenger level of service when setting a timetable. Therefore, it will be helpful for transit agencies to better understand the relationships between schedule parameters (schedule time, necessary recovery time, and frequency) and operating cost and passenger service level in choosing the timetable that would be optimal for their objectives.

Implementation of operations control strategies presents a further complication. Operational control strategies such as holding and signal priority treatment directly change the mean and variability of running time, which are critical in setting the scheduled running time and necessary recovery time. Therefore a schedule that is optimal without operational controls may not be optimal when operational controls are applied on a route. For example, if a holding strategy is implemented on a route, longer schedule running time and shorter recovery time than before will be needed due to increased running time and on-time performance (in terms of improvement of speed and reliability). Therefore, research is needed to help find the combination of schedule parameters (schedule time, recovery time, and frequency) that meets operator and passenger objectives when operations control strategies are implemented.

1.2. Objectives

The principal objectives of this research are therefore:

1) to understand the relationships between schedule parameters, operational cost, passenger demand, and service quality.
2) to develop a process for selecting the schedule parameters and apply it to a specific bus route.
3) to demonstrate how these relationships affect the timetable setting process through application to a specific bus route.

1.3. Literature Review

Muller and Furth (2000) show how service planning can be integrated with operational control using simple illustrations based on the system implemented in Eindhoven, the Netherlands. First, they present the impact of operations control on improving service quality. In their research, they use holding strategy at time points and conditional traffic signal priority at signalized intersections as operations control strategies. They found that these operations control strategies do indeed help reduce schedule deviation, thus reducing passenger wait time. This research also shows the way that data gathered using on-board computers can be analyzed and used to help create a better schedule. TRITAPT (TRIp Time Analysis for Public Transport) is used for data analysis and to plan the schedule. Finally, they show the improvement in service performance which can be achieved by integrating operations planning and operations control. This research resulted in a feasible schedule which trades off speed and schedule variation.

Wirasinghe and Liu also studied transit route schedule design in their papers. In the paper, Optimal Schedule Design for a Transit Route with One Intermediate Time Point (1995), they showed that the decisions on the number and locations of time points and the scheduled travel times between adjacent time points are important in schedule design for a route. The optimal amount of slack time and whether the time point is necessary are determined by minimizing the expected total cost, which consist of operating cost, passenger waiting cost, and delay cost. In this paper, they found out that the optimal design of a schedule is sensitive to the passenger demand pattern along the route and that a time point is needed only when the number of boarding passengers is much larger than the number of through passengers. They also developed a simulation model of schedule design for a fixed transit route using the holding control strategy (2001). The location of time points along the route and the amount of slack time at each time point can be determined using the simulation model by minimizing total cost associated with the schedule. They demonstrated the potential savings from the model through application to a route of Calgary Transit.

There have also been several efforts to develop dwell time models. In general, these have used ordinary least squares regression to derive the dwell time as a function of the numbers of passengers boarding and alighting and other operating characteristics such as fare payment method, seat availability, and number of doors used for boarding and alighting. Lin and Wilson (1993), in their dwell time relationships analysis, developed dwell time models for one-car and two-car light rail operations. The result of those models showed that the number of passengers boarding and alighting and passenger "friction" caused by the passengers already on board significantly affects the dwell time. Several forms of passenger friction term based on the number of standees, were tested and proved to significantly affect the dwell time. Aashtiani and Iravani (2002) developed various dwell time models as a function of passenger volume, which were used in the City of Tehran transit assignment model. Two types of models are considered in their research: one is a disaggregate model which attempts to estimate the dwell time at each stop and the other is an aggregate model which attempts to estimate the total dwell time for all the stops on the route. Number of passengers boarding and alighting, load factor, and some bus characteristics such as capacity and number of doors were considered as variables which may influence the dwell time.

Furth (1980) reviewed both practical and theoretical approaches to set the service frequency and developed a model to solve this problem. The model assigned the available vehicles between time periods and between routes so as to maximize the benefit under constraints on subsidy, fleet size and levels of vehicle loading. He showed that this problem can be formulated either as a fixed demand minimization of total expected passenger waiting time or as a variable demand consumer surplus maximization with very similar results. Koutsopoulos (1983) also formulated the problem of setting frequency as a nonlinear mathematical program with the objective of minimizing the social cost including passenger waiting times, crowding levels, and operational costs under constraints on the fleet size, vehicle capacity, and subsidy.

Some of the previous research reviewed is similar to the proposed research in that it dealt with the impacts of decisions on specific schedule parameters on various costs. In general, they tried to find an optimal value for a schedule parameter by minimizing the total cost when other schedule parameters were fixed. Wirasinghe and Liu studied the impacts of schedule time and Furth and Koutsopoulous studied those of frequency. By developing different forms of dwell time models, the relationship between passenger demand and dwell time has been studied which leads to the relationship between frequency and dwell time.

This research considered the decision on each schedule parameter independently. Therefore, they tried to optimize the specific schedule parameter based on the schedule parameters determined at the previous steps being a fixed input at the current step. So, the full set of relationships between schedule parameters have not been considered. However, schedule parameters affect the operational cost and passenger service levels, and furthermore changes in one schedule parameter can influence decisions on other schedule parameters. Therefore, it is important to understand the possible impacts of schedule parameter change as well as the general relationships between schedule parameters, operational cost and service quality. In this research, I will develop the relationships between schedule parameters, service quality and operational cost and also develop an effective scheduling process, which enable the schedule parameters to interact with each other and thus enable the transit operator to find combinations of schedule parameters which better meet their objective.

1.4. Research Approach

The primary goal of this thesis is to understand the relationships between schedule parameters, operational cost, and service quality that can help transit agencies in developing more effective timetables. The relationships are developed from an analytical model of a simplified bus route incorporating a holding strategy at time points. First, an analytical model to estimate the trip time distribution with different scheduled departure times at the time points and different numbers of time points is developed. And a dwell time model is built to assess the impact of headway changes on the trip time distribution. Second, the impacts of changes in the trip time distribution caused by the change of one scheduled parameter on the other scheduled parameters are explored. Third, the relationships between the operational cost and the schedule parameters are derived by developing a cost model, which is a function of the schedule parameters. Finally, the impacts on service quality of possible changes in the scheduled parameters are estimated.

A case study of a Chicago Transit Authority bus route will be used to demonstrate the relationships that were included in the analytical model through application of these relationships to the scheduling process of a specific bus route. In order to estimate the trip time distribution changes resulting from schedule time and headway changes, the trip time estimation model and the dwell time model developed in the theoretical analysis are estimated and applied. The case study will also show the tradeoff between the operational cost and service quality when different combinations of schedule parameters are chosen.

1.5. Thesis Organization

This thesis is organized into five chapters. Chapter Two provides a general introduction to operations planning and definitions of schedule parameters, operational cost, and service quality. The inter relationships existing in the schedule parameter setting process are also discussed. Chapter Three develops the theoretical relationship models, which exist between the schedule parameters, operational cost, and service quality. A scheduling process to incorporate these relationships is proposed. Chapter Four presents the case study of CTA route 77, Belmont. The general theoretical relationship models are applied to the scheduling process of CTA route 77 during the AM peak and the tradeoffs between operational cost and service quality with different combinations of schedule parameters are estimated and presented. Chapter Five summarizes and discusses the findings and makes recommendations for future research.

Chapter 2. Bus Operations Planning

This chapter describes the typical operations planning process and defines the key parameters which are established in this process. Section 2.1 gives an overview of service and operations planning. The research focuses primarily on the analysis of relationships involved in setting schedule parameters for a single bus route. Since setting the schedule parameters is at the heart of the vehicle and crew scheduling processes, these decisions largely determine both the costs to the transit agency and the service quality to the passengers. In section 2.2, the definitions of schedule parameters, operational cost, and service quality that will be used in this research are provided and the relationships between them that should be considered in the process of setting the scheduling parameters are discussed.

2.1. Operations Planning Overview

Designing a transit service involves a series of decisions, which are illustrated in Figure 2-1. The main stages in the planning process are designing the network, setting service frequency and span, developing the timetable, scheduling vehicles and scheduling crews. Typically these steps are solved sequentially with each decision being made based on the decisions made in the previous steps. The planning process can also be divided into service planning and operations planning. Network and route design, service frequency setting, and timetable development are included in the service planning process and vehicle and crew scheduling are included in the operations planning process.

In the network design step, given the demand characteristics, infrastructure, resources and coverage policies, a set of routes is determined. Next, service frequencies by time of the day and service span of each route are decided according to demand characteristics, available vehicles, available budget, and headway and passenger load policies. In the step of developing a timetable, based on the route travel time data and service policies related to service quality, the schedule time and recovery time are set. In the vehicle scheduling step, given a timetable, vehicle blocks (a sequence of revenue and non-revenue activities for each vehicle) covering all trips are scheduled. Given the vehicle scheduling outputs, which are the set of vehicle blocks, crews runs are developed each consisting of several pieces of work from one or more vehicle blocks.

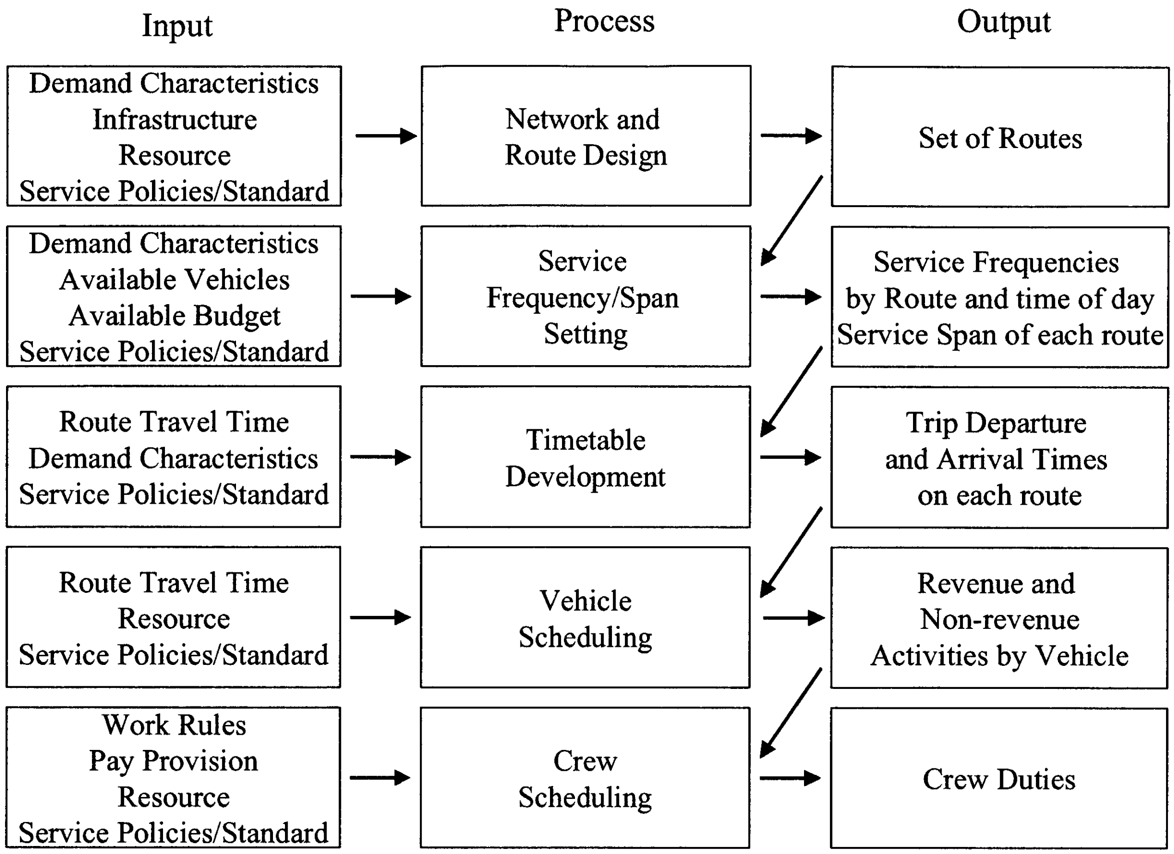


Figure 2-1 Service and Operations Planning Hierarchy

As shown in Figure 2-1, there are service standards and/or policies involved in decision-making at each step of the transit service planning process. These service standards and policies are designed to provide a balance between optimal cost efficiency, which is the interest of transit agencies, and the provision of adequate service to the public, which is the interest of passengers. The next five sections summarize the typical service and operations planning process and the role that service standards and policies play. This discussion is based on the TCRP Report 30, Transit Scheduling: Basic and Advanced Manual (1998).

2.1.1. Network Design

Route design is basically the definition of where each route goes. Again, service policies and standards generally dictate the type of balance between cost efficiency and service to the public in designing the network. The following are usually considered as the basics of network design standards: population density, employment density, spacing between routes/corridors, limits on the number of deviations or branches, and coverage. Network and route design typically evolve very slowly over time, partly because of the difficulty of the network design process and partly because agencies are often reluctant to change existing routes for fear of alienating current riders. Network re-design is undertaken only rarely and often only when major capital investments necessitate it.

2.1.2. Service Frequency/Span Setting

The span of service is the duration of time that vehicles provide passenger service on a route. It is measured from the time of the first trip on the route to the time of the last trip on that route. It is also often established by service policies and standards influenced by the demand for services.

The route frequency defines the headway, the time interval between two consecutive revenue vehicles operating in the same direction on a route. It is determined either by policy or by demand as reflected in factors such as the maximum passenger load. For this purpose, a maximum load point is defined as the location along a route where the greatest number of passengers are on board. With data on maximum load point counts, the scheduler can determine the number of vehicles that are needed to accommodate the passengers wanting to use the service given maximum acceptable passenger loads per vehicle.

The demand-based headway is determined based on the maximum load point counts, vehicle capacities, and loading standard, which indicates how many people can be on board at certain times and on certain vehicles. The load standard is expressed as the ratio of passengers allowed on the vehicle to the actual seating capacity of the vehicle expressed as a percentage. If demand is very low then a policy-based headway is set based on the minimum level of service on the route as reflected in the service standard.

2.1.3. Timetable Development

Developing a timetable involves setting the schedule time on a route given the headway determined in the frequency setting step based on the data (trip time, passenger demand, etc) and constraints (number of buses available, subsidy available, etc). Trips are generated based on the selected schedule parameters (frequency and schedule time). The timetable indicates all the times that vehicles are scheduled to pass each time point along the route.

Schedule time is the number of scheduled minutes assigned to a revenue vehicle to move from one time point to the next with time points being locations along the route, with posted bus arrival (or departure) times. Major intersections that are widely recognized and have good pedestrian access are usually selected as time points. These points usually have high levels of passenger demand. Usually, the schedule time is set to the average running time between time points.

2.1.4. Vehicle Scheduling

Vehicle scheduling is the process of assigning vehicles to the trips generated in the timetable development process. A series of trips is assigned to a single vehicle and is called a "vehicle block." The objective of the vehicle scheduling step is to define vehicle blocks (a sequence of revenue and non-revenue activities for each vehicle) covering all trips so as to minimize fleet size and non-revenue vehicle time under the constraint of minimum and maximum vehicle block length. The agency policies that have the greatest impact on the vehicle scheduling process are recovery time and interlining policies and constraints.

For many agencies, on some or all routes, the amount of recovery time is often determined either by labor agreement or agency policy. These agreements or policies dictate a minimum number of minutes that must be built into the schedule for recovery time. Usually, the minimum recovery time is set to a certain percent of route trip time and many transit agencies use a minimum recovery time of 10 percent of round trip time.

The cycle time is the number of minutes needed to make a round trip on the route, including recovery time. Minimum cycle time is the number of minutes scheduled for the vehicle to make a round trip, including a minimum recovery time.

2.1.5. Crew Scheduling

Crew scheduling is the process of defining crew assignments. First, runs are assembled or cut from the vehicle blocks generated in the vehicle scheduling phase of the process. A single crew is assigned to a run, which consists of one or more complete or partial blocks. The objective of crew scheduling is to define crew duties covering all vehicle block time so as to minimize crew costs under the constraints of work rules, policies, and crew availability. The work rules and policies considered in the crew scheduling process are minimum and maximum platform time, report and turn-in allowances, spread time and spread penalty, run type percentages, and make-up time.

2.2. Schedule Parameters in Operations Plan

Schedule parameters, which include service frequency, schedule time, and recovery time, are determined in the process of service and operations planning. Before providing the brief introduction of the relationships between schedule parameters, operational cost, and service quality, it is necessary to define these terms as they will be used in this research. The primary schedule parameters considered in this thesis are headway (alternatively frequency) and cycle time (the sum of schedule time and recovery time). The scheduled time and recovery time, components of the cycle time are analyzed separately when needed. The headway is the time interval between successive bus arrivals (departures) in the same direction on a route. The cycle time is defined as the time it takes to drive a round trip on a route plus any time that the operator and vehicle are scheduled to take a break before starting out on the next trip. The schedule time is the number of scheduled minutes assigned to a vehicle for moving from one time point location to the next. The time allowed to make a one-way trip is the scheduled trip time. Recovery time is "buffer" break time built into the schedule. Therefore, if the vehicle is behind schedule, recovery time can be used to catch up to the schedule by not taking the full scheduled recovery time.

The operational cost includes the direct costs and the additional cost resulting from late trips. The direct cost includes driver wages, fuel costs, and maintenance costs, which are associated with travel time per trip, travel miles per trip and number of trips operated. The additional cost is associated with the actual trip times, the number of late trips, and the unit delay costs.

There are several possible measures for evaluating service quality reflecting service speed, reliability, and crowding. Passenger in-vehicle time reflects the speed of vehicles. Passengers are interested in minimizing their travel time, preferring short in-vehicle time: as passenger in-vehicle time decreases, service quality improves. Schedule adherence and passenger out of vehicle time reflect reliability of service. Transit agencies usually use schedule adherence for evaluating their service performance however, improvements in schedule adherence do not necessarily bring about improvement in service reliability from the passenger perspective. If passengers arrive at a bus stop regardless of bus schedule, as is typical for high frequency service, passenger do not care whether buses are on schedule or not as long as buses come at regular intervals. Thus, passengers usually evaluate transit service reliability in terms of waiting time since waiting time tends to be more uncertain and more uncomfortable. Since the interests of passengers and transit agencies in terms of transit reliability are somewhat different, I consider these two as measures to represent service reliability. Crowding level is one measure to evaluate comfort level in a bus. Crowding level is the most important element among other elements that determine comfort level since it has great influence on operations as well. Passenger crowding in the vehicle can negatively affect overall operations as well as passenger comfort level while other comfort factors such as seating quality, cleanliness of vehicle and so on just determine passenger comfort level. High crowding levels cause longer dwell time due to difficulty in boarding and alighting, and thus increase vehicle trip time and variability. Therefore, crowding level can measure not only the crowding aspect of comfort, but also an important influence on reliability and in-vehicle time.

The operating plans at the route level and network level have different focuses. The operating plan at the network level focuses on problems such as interlining, schedule synchronization and transfers between routes. The operating plan at the route level focuses on recognizing and dealing with the stochastic nature of each route, including stochastic passenger arrivals, bus arrivals, passenger boarding and alighting processes, reliability and control strategies. Therefore, for planning a single bus route, the operating plan focuses on the steps of setting frequency and developing timetable, in other words, setting the schedule parameters. As discussed above, decisions on setting schedule parameters are heavily influenced by the transit agency's service standards and policies. Service frequencies by time of day are determined based on maximum policy headway and maximum passenger peak load. After setting service frequencies, the schedule time and necessary recovery time are determined based on the route travel time data and service policies that may affect them. Usually, the schedule time is set to the average trip time and recovery time is set to a certain percent of the average trip time.

Different setting of the schedule parameters will result in different operational cost and service quality. There will be specific setting of the schedule parameters, which reflect the tradeoff between service quality and operational cost, embedded in the agency's objective. However, with the traditional scheduling process, we just determine the schedule parameters which satisfy the general agency's standards, and thus provide a minimum service quality. This means that there is no easy way to assess the operational cost and service quality with different schedule parameters and find better schedule parameters for a route. Also, the influence of a decision on one schedule parameter on the other schedule parameters is not considered in current scheduling process. Figure 2-2 shows the inter-relationships between schedule parameters, which should be considered in a general scheduling process. The gray elements are the schedule parameters that the operator can control in the scheduling process.

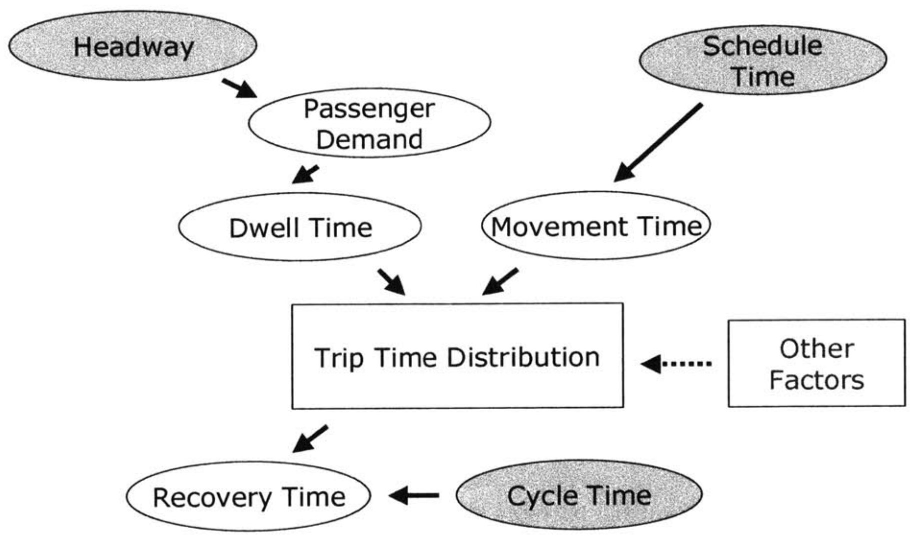


Figure 2-2 Inter-relationships between Schedule Parameters

Vehicle trip time consists of dwell time and movement time. The dwell time will be affected by the vehicle headway since the vehicle headway determines the passenger demand at bus stops and passenger demand determines the dwell time at each stop. The vehicle movement time will be affected by the schedule time when a schedule-based holding strategy is implemented since the vehicle should not depart from the time points until the scheduled departure time. Therefore, the trip time distribution will change depending on the headway and schedule time. The half cycle time is determined by the on-time departure probability at the terminal that the transit agency wants to achieve based on the trip time distribution. The recovery time is then simply set to the difference between the half cycle time and the schedule time. In other words, the half cycle time and recovery time are determined from the desired on-time departure probability and the trip time distribution that is determined by the schedule time and headway. Therefore, any changes in the headway and schedule time will influence decisions on other schedule parameters, specifically the half cycle time and recovery time.

The operational cost and service quality are also affected by the schedule parameters. Figures 2-3 and 2-4 show the relationship between operational cost and schedule parameters and the relationship between service quality and schedule parameters respectively.

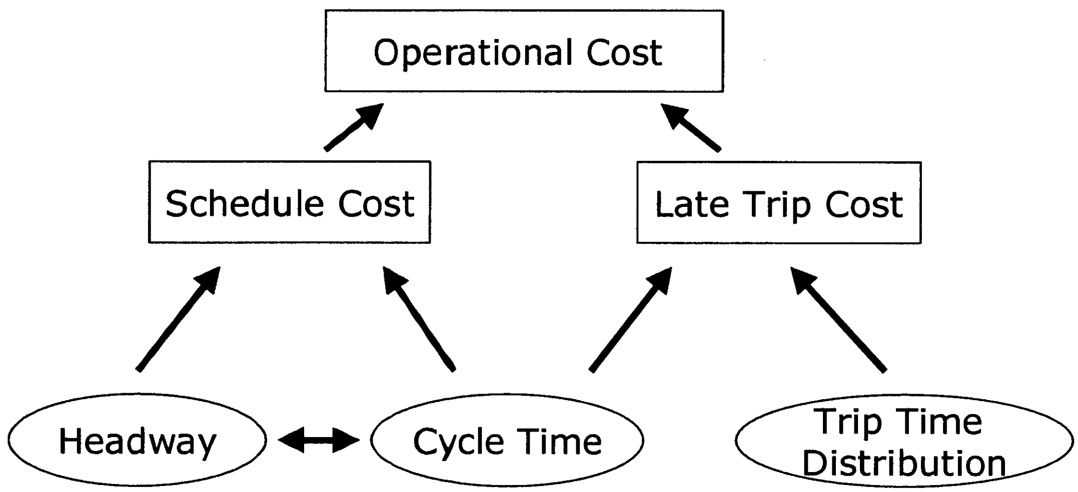


Figure 2-3 The Relationship between Operational Cost and Schedule Parameters

The operational cost includes both the schedule cost and cost of any late trip. The schedule cost during a time period is determined by the cycle time and headway, which determines the number of vehicles needed during the time period. The late trip cost is generated only if the operator has to work overtime, that is the total work time is greater than the scheduled work time. Since the total work time distribution for each piece of work consists of the trip time distributions of trips and the scheduled work time is based on the vehicle cycle time, the late trip cost will depend on the trip time distribution and cycle time.

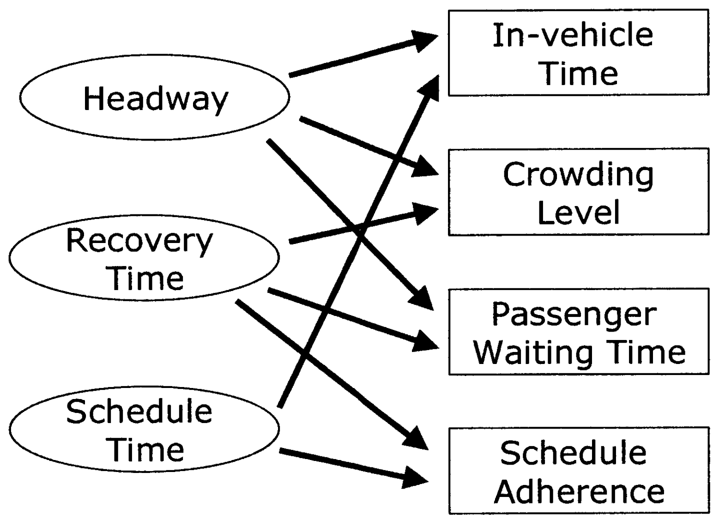


Figure 2-4 The Relationship between Service Quality and Schedule Parameters

The service quality is measured by the in-vehicle time, crowding level, passenger waiting time, and schedule adherence. Passenger in-vehicle time is determined by the actual trip time. Since the trip time is affected by the headway and schedule time, the passenger in-vehicle time is affected by the headway and the schedule time. Crowding level is mainly determined by the vehicle headway since the headway determines the passenger demand at the stop. Also, by controlling the departure headway at the terminal, the recovery time can influence the passenger demand at the stop, and thus the crowding level. The passenger waiting time is determined by the headway distribution, average headway and headway variability. Average headway will be mainly affected by the schedule headway and the headway variability is affected by the recovery time. Therefore, the passenger waiting time is affected by the headway and recovery time. The schedule adherence is measured by the on-time arrival probability at the ending terminal and on-time departure probability at the starting terminal. The on-time arrival probability is determined by the schedule time and the on-time departure probability is determined by the recovery time. Therefore, schedule adherence is affected by the schedule time and recovery time.

In this chapter, I have reviewed the current service and operations planning process and the relationships between schedule parameters, operational cost, and service quality that will affect the decision on the schedule parameters. After deriving the relationships for a simplified route in Chapter 3, I will develop an alternative schedule parameters setting process, which incorporates the relationships between the schedule parameters, operational cost and service quality.

Chapter 3. Theoretical Analysis of Relationships between Schedule Parameters, Operational Cost, and Service Quality

In this chapter, I derive the relationships between schedule parameters, service quality and operating cost for a general bus route having stops between a starting terminal and an ending terminal. The resulting relationships, which are developed for a simplified route with many assumptions, should be similar to those for a more complex route. By deriving the relationships for a simplified route, we can better understand the general relationships between the schedule parameters, service quality and operational cost. Before developing the relationships, the simplified route and the basic assumption made in this analysis are described. In section 3.2, the impact of schedule parameters on the trip time is developed. The inter-relationships between the schedule parameters are discussed in section 3.3, and the relationships between the operational cost and schedule parameters and the relationships between service quality and schedule parameters are developed in sections 3.4 and 3.5 respectively. In section 3.6, a revised scheduling process, which incorporates the relationships between schedule parameters, operational cost and service quality, is proposed.

3.1. Route Description and Basic Assumption

A simple bus route with a starting terminal A, and an ending terminal B is considered (see Figure 3-1). There are k time points ($P_1, P_2, \ldots, P_k$) between the starting and ending terminal along the route of length d and buses run every h minutes. The basic assumptions are described below:

1. The passenger arrival rate is constant over the time period.
2. All passengers can board the first bus to arrive, i.e. the capacity constraint is not binding.
3. Successive runs are completely independent of each other.
4. The segment time (T_i) is a random variable with mean, $E(T_i)$, and standard deviation, $\sigma(T_i)$.
5. The trip time distribution is affected by the choice of scheduling parameters.

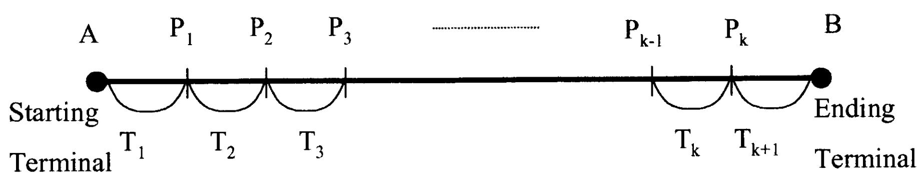


Figure 3-1 A Route with k Possible Time Points

Though these assumptions are made to simplify the problem and thus make it easy to build the relationships between schedule parameters, operational cost and service quality, they may result in an inaccurate representation of actual operating conditions. With the second assumption, we cannot consider the case that passengers may not be able to board the first bus and thus have to wait for the next bus, which can happen during the peak time for high frequency service. Thus this assumption may under-estimate the passenger waiting time by ignoring the extra time waiting for the next bus. The fourth assumption further implies that segment times are independent of each other. However, in real operations, a driver tends to drive faster in the current segment if he or she was late in the previous segment. Therefore, typical driver behavior is neglected in this assumption.

The assumption that successive runs are completely independent of each other makes it possible to schedule one run at a time and thus to derive the relationship between the schedule time and the trip time distribution. However, since this assumption implies that headway variability does not affect the overall operations much and further implies that the dwell time is not affected by headway, it cannot represent the operating condition of high frequency service. For a low frequency bus route, the headway variability does not change the passenger demand at the stop since the passenger arrives at the stop based on the schedule and thus the dwell time can be constant. For a high frequency bus route, the dwell time, which is included in trip time, is affected by the actual headway due to different passenger demand per bus. Therefore, with this assumption, we cannot consider the randomness of dwell times in high frequency service.

From this assumption, the difference in control strategies between high frequency service and low frequency service can be discussed. For a low frequency route, the service performance is mainly measured by the schedule adherence since passengers arrive at the stop based on schedule and thus service quality is usually controlled by the schedule. However, for a high frequency route, since the headway affects the operations a lot by changing the passenger demand on a bus and passengers arrive at stops randomly, service performance is mainly measured by the passenger waiting time. Thus, service quality is controlled through the headway with real time operations control strategies such as holding.

3.2. Trip Time Distribution and Schedule Parameters

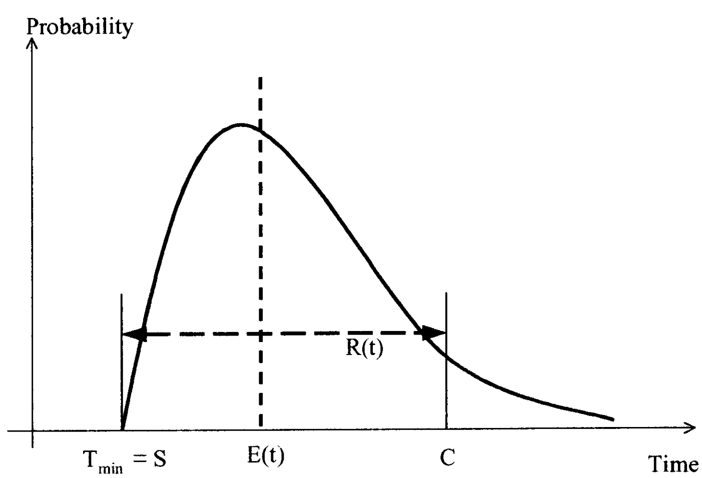
Vehicle trip time can be divided into vehicle movement time and dwell time. The dwell time will be affected by the passenger demand on the route since more time is required to handle boarding and alighting passengers as passenger demand increases. The vehicle movement time will be affected by the schedule time when schedule-based holding is implemented since the vehicle should not depart until the scheduled departure time at each time point. Therefore, the trip time, which is the sum of vehicle movement time and dwell time, will change as the schedule parameters change. In this section, I will show how the trip time distribution will change according to the changes of schedule time and headway by developing an analytical model which represents the relationship between the arrival time at a time point and the schedule departure time at the previous time point and a dwell time model which represents the relationship between dwell time and passenger load (since headway determines the passenger load, given the assumption that the passenger arrival rate is constant, it can be a relationship between dwell time and headway).

3.2.1. The Influence of Time Points and Schedule Time on Trip Time

The one-way trip time is measured from the moment the bus departs the starting terminal to the moment it arrives at the ending terminal. The trip time will be a random variable with mean $E(T)$, and standard deviation $\sigma(T)$ when the schedule has a tight scheduled trip time, which is set to the minimum trip time (see Figure 3-2). In this case, there is no schedule constraint effect in the trip time, which means that vehicles leave bus stops as soon as the passenger alighting and boarding processes are completed. Since every trip time is longer than the tight scheduled trip time, the recovery time is the only way to maintain a certain level of service quality by controlling on time departure probability for the following trip.

For a low frequency bus route, the headway variability does not change the passenger demand at the stop since the passenger arrives at the stop based on the schedule. Therefore, the unconstrained trip time distribution obtained from a low frequency bus route should be free from headway variability. However, the unconstrained trip time distribution obtained from a high frequency route will be affected by the headway distribution since the headway determines the passenger demand at the stops and thus affects the dwell time. If the headways are fairly even, the trip time distribution will be tighter while if it is not the trip time distribution will be wider. Short trip times are likely to occur with short headways and long trip times are likely to occur with long headways. Therefore the observed trip time distribution should be adjusted in order to make it free from the headway variability in case of high frequency service.

As discussed in Chapter 2, movement time is not affected by the headway while dwell time is. If we know the vehicle dwell time and movement time separately, we can modify the trip time distribution by first extracting the movement time. If we assume that the passenger arrival rate is constant over a time period, we might also assume that the dwell time of each trip will be constant if there is no headway variability. Therefore, we could get the adjusted trip time distribution, which is unaffected by the schedule time and headway, by adding the constant dwell time to the movement time distribution. However, it is more realistic to consider that the dwell time to be a random variable rather than a constant even if there is no headway variability. The dwell time distribution could be obtained from the observed data with some modification of extreme values caused by long (short) headways or with an assumption that the mean dwell time is the same but the variance is decreased if the headways are more even. The adjusted trip time distribution could be obtained by adding the movement time distribution and modified dwell time distribution.



T_{min}: Minimum Trip Time

E(t): Expected Trip Time

S: Scheduled Trip Time

R: Recovery Time

C: Half Cycle Time

Figure 3-2 Unconstrained Trip Time Distribution

The adjusted trip time distribution should be skewed to the right with a lower bound T_{min}, since it is impossible for a bus to travel along a route faster than a certain speed. However, it is possible to have a much longer than expected travel time due to traffic conditions, incidents and so on although the probability would be very low. Theoretically, the distributions having those characteristics could follow a gamma distribution (Turnquist and Bowman, 1980) or a lognormal distribution (Andersson and Scalia-Tomba, 1981).

However Figure 3-2 is unrealistic because the tight scheduled trip time is not practical due to its poor resulting service quality (low on time arrival probability) at stops along the route. Thus, the transit agency would want to have a longer scheduled trip time than the minimum. If the transit agency increases scheduled trip time without doing anything else, it will just increase the probability that vehicles are early. Moreover, for low frequency service, early arrival can be worse than late arrival since it could cause passengers to miss their targeted buses and experience very long waits. Therefore, it will not be better than the previous case of tight scheduled trip time. A holding strategy is used to prevent early departures by holding early vehicles at the time point until the scheduled departure time, thus increasing the schedule adherence. Therefore, as the scheduled trip time is increased, more holding to meet the schedule is required. In my research, I assume that schedule-based holding is implemented whenever the scheduled trip time is longer than the minimum trip time to prevent early departures from time points.

When the holding strategy is implemented, the trip time distribution is affected by the scheduled trip time. Since a vehicle which arrives early at a time point will wait till the scheduled departure time, most trips, which arrive earlier at the terminal than the scheduled arrival time without holding, will arrive close to the scheduled time with holding. However, some of these trips would not arrive at the terminal on time since there is less time to catch up with the schedule if the vehicle is delayed near the ending terminal. Therefore, the probability of late arrival at the terminal will increase with holding. When the scheduled time is increased and consequently the scheduled departure times at time points increase, the probability that a vehicle arrives at the ending terminal late will also increase. Therefore, the trip time distribution will have a longer expected trip time and tail. The trip time distribution will also be affected by the number of time points along the route. As the number of time points increases, more time is spent holding a vehicle, and thus there will be less time for catching up with schedule. Therefore, more time points will cause a higher expected trip time for a given scheduled time. In order to understand how the schedule time and holding strategy affects trip time distribution, I will derive the arrival time distribution at the ending terminal when the holding strategy is implemented initially at only one time point (see Figure 3-3).

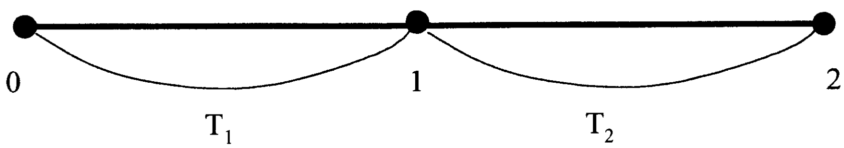


Figure 3-3 Route with One Time Point

The segment time, T_i, i = 1, 2 is measured from the moment the bus leaves point i-1 to the moment the bus arrives at point i and is assumed to be a random variable with mean $E(T_i)$, and standard deviation $\sigma(T_i)$. The vehicle arrival and departure times for point i, are T_{ai} and T_{di} respectively and scheduled departure time for point i is S_i. With the assumption that every bus departs on time at the starting terminal, then S_0 is both the actual departure time and the scheduled departure time for point 0 and is set to 0. For the ending terminal, S_2 will be the scheduled departure time for the next trip, and thus S_2-T_{a2} will be the recovery time. Since the scheduled departure time is set to 0, the vehicle arrival time at point 1, T_{a1}, will be the same as T_1. The vehicle arrival time at point 2, T_{a2}, will be the sum of the actual departure time at point 1, T_{d1}, and the segment running time between 1 and 2, T_2. Therefore, the relationships between arrival time and departure time between stops are:

$$T_{a1} = S_0 + T_1 = T_1 \tag{3-1}$$

$$T_{a2} = T_{d1} + T_2 \tag{3-2}$$

Since the vehicle does not depart before the scheduled departure time at time point 1, the vehicle departure time will be the scheduled departure time if the vehicle arrives earlier than the scheduled departure time or the vehicle arrival time if the vehicle is late. Note here that the dwell time is assumed to be included in the segment time.

$$T_{d1} = \begin{cases} S_1 \text{ , } if\, T_{a1} < S_1 \\ T_{a1} \text{ , } if\ T_{a1} \geq S_1 \end{cases} \tag{3-3}$$

We can estimate the expected departure time and the variance of departure time at time point 1 as follows:

$$E(T_{d1}) = \int_{S_1}^{\infty} t f_{T_{a1}}(t)dt + S_1 * (1 - \int_{S_1}^{\infty} f_{T_{a1}}(t)dt) \quad (3\text{-}4)$$

$$D^2(T_{d1}) = \int_{S_1}^{\infty} t^2 f_{T_{a1}}(t)dt + S_1^2(1 - \int_{S_1}^{\infty} f_{T_{a1}}(t)dt) - \{E(T_{d1})\}^2 \quad (3\text{-}5)$$

The first term of $E(T_{d1})$ is the expected departure time when the vehicle arrives at the time point late and the second term is the product of the probability that the vehicle arrives earlier than the scheduled departure time and the scheduled departure time itself. The expected departure time at the time point, $E(T_{d1})$, increases and the variance of T_{d1} decreases as the scheduled running time increases according to the equations above.

The probability density function of departure time at time point 1, T_{d1} can be derived as follows:

$$F_{T_{d1}}(t_{d1}) = P\{T_{d1} \le t_{d1}\} = P\{T_{a1} \le t_{d1}\} = F_{T_{a1}}(t_{d1}) \qquad T_{a1} \ge S_1 \quad (3\text{-}6)$$

and thus

$$f_{T_{d1}}(t_{d1}) = F'_{T_{d1}}(t_{d1}) = f_{T_{a1}}(t_{d1}) \qquad T_{a1} \ge S_1 \quad (3\text{-}7)$$

Due to holding to the schedule, the probability distribution of T_{d1} has a discrete mass at S_1.

$$P\{T_{d1} = S_1\} = P\{T_{a1} \le S_1\} = F_{T_{a1}}(S_1) \qquad T_{a1} < S_1$$

Therefore, the probability distribution of T_{d1} has a spike at S_1 and the distribution remains the same as the distribution of arrival time at point 1, T_{a1}, when $T_{a1} \ge S_1$.

From the relationship between the vehicle arrival time at point 2, T_{a2}, and the departure time at point 1, T_{d1} (see Equation 3-2), we can derive the expected arrival time and variance of arrival time at the ending terminal. The distribution of arrival time at the ending terminal will be the trip time distribution of the route. With the assumption that the segment running time between points 1 and 2, T_2, is independent of the departure time at time point 1, T_{d1}, the expected mean arrival time and variance of vehicle arrival time at the ending terminal can be derived as:

$$E(T_{a2}) = E(T_{d1}) + E(T_2) \quad (3\text{-}8)$$

$$D^2(T_{a2}) = D^2(T_{d1}) + D^2(T_2) \quad (3\text{-}9)$$

Since T_{d1} and T_2 are assumed to be independent of each other, their joint density function can be obtained simply by multiplying their distributions:

$$f_{T_{a1}}(t_{d1}) * f_{T_2}(t_2) \qquad T_{d1} \geq S_1 \quad (3\text{-}10)$$

Also, the joint distribution, when the vehicle arrives at time point 1 earlier than scheduled, will be the product of the probability that vehicle arrives on time at the time point 1 and the probability that T_2 is t_2:

$$P\{T_{d1} = S_1, T_2 = t_2\} = P\{T_{d1} = S_1\} * P\{T_2 = t_2\} = F_{T_{a1}}(S_1) * f_{T_2}(t_2) \qquad T_{a1} < S_1 \quad (3\text{-}11)$$

The cumulative density function of T_{a2} is:

$$F_{T_{a2}}(t_{a2}) = P\{T_{a2} \leq t_{a2}\} = F_{T_{a1}}(S_1) * P\{T_2 \leq t_{a2} - S_1\} + \iint_R f_{T_{a1}}(t_{d1}) * f_{T_2}(t_2) dt_2 dt_{d1}$$
$$= F_{T_{a1}}(S_1) * \int_{T_{2\min}}^{t_{a2}-S_1} f_{T_2}(t_2) dt_2 + \int_{T_{2\min}}^{t_{a2}-S_1} \int_{S_1}^{t_{a2}-t_2} f_{T_{a1}}(t_{d1}) * f_{T_2}(t_2) dt_{d1} dt_2 \quad (3\text{-}12)$$

The probability density function of T_{a2} can be derived by differentiating the cumulative density function (Equation 3-12) with respect to t_{a2}.

$$f_{T_{a2}}(t_{a2}) = (1 - \int_{S_1}^{\infty} f_{T_{a1}}(t_1) dt_1) * f_{T_2}(t_{a2} - S_1) + \int_{T_{2\min}}^{t_{a2}-S_1} f_{T_{a1}}(t_{a2} - t_2) * f_{T_2}(t_2) dt_2 \quad (3\text{-}13)$$

The first term represents the probability when the vehicles are on time at time point 1 and the second term represents the probability when they are late.

As shown above, the arrival time distribution at the terminal, which is the trip time distribution of the route, can be expressed as a function of the scheduled departure time at the time point given the segment time distributions. When the schedule time increases and consequently the scheduled departure time at point 1 increases, the probability that the vehicle arrives at the ending terminal, t_{a2}, on time will increase. Simply put, the expected arrival time at the ending terminal increases since it is the sum of $E(T_{d1})$ and $E(T_2)$, and $E(T_{d1})$ increases with increase of scheduled departure time. Due to the increase of schedule time, the variance of arrival time at the ending terminal is reduced. As shown above the variance of departure time is reduced as the scheduled running time increases. Since the variance of arrival time, $D^2(T_{a2})$ is the sum of $D^2(T_{d1}) + D^2(T_2)$, it is also reduced with increasing schedule time.

This model derives the trip time distribution when there is one holding point on the route. However, the probability density function of T_{a2} can be a general function for the vehicle arrival time distribution at the second of any two time points. Therefore, we can extend the model to a route having multiple time points. By using the vehicle arrival time function depending on the scheduled departure time at the previous time point and trip time distribution between two adjacent time points (Equation 3-13), a spreadsheet model was built to estimate the vehicle arrival distribution at the terminal given different numbers of holding points and scheduled times.

The schedule departure time of each time point is determined by the desired on time arrival probability at the time point. For example if the desired on time arrival probability is 85 percent, the schedule trip time is set to the 85 percentile of cumulative time to that time point in the unconstrained segment time distribution. Therefore, when the segment time distributions between adjacent time points are all identical, the scheduled segment times should be the same for all segments. However the schedule time of the last segment will not affect the trip time distribution. The on time departure probability for the next trip is affected by the half cycle time rather than the scheduled time for the last segment. Therefore, the scheduled time for the last segment is assumed to be always set to the average segment trip times while other segment times are decided based on the desired on time arrival probability.

In order to show the change in the trip time distribution as functions of the change of the schedule time and number of time points, Figures 3-4 and 3-5 are generated from this model. It is assumed that there are 5 possible holding points (points 1 through 5), which are distributed evenly along the route and the segment time distributions between adjacent time points are all identical.

The unconstrained segment time distribution is assumed to follow a gamma distribution having 10 minutes, 3, and 1 as minimum segment time, α value, and β value respectively. This distribution has a mean of 13 minutes and a variance of 3 minutes from those parameters. The holding points according to the different number of time points are listed in Table 3-1.

Number of Time Points	Holding Point Location
1	Point 3
2	Point 2, Point 4
3	Point 1, Point 3, Point 5
5	Point 1, Point 2, Point 3, Point 4, Point 5

Table 3-1 Holding Points Locations with Different Number of Time Points

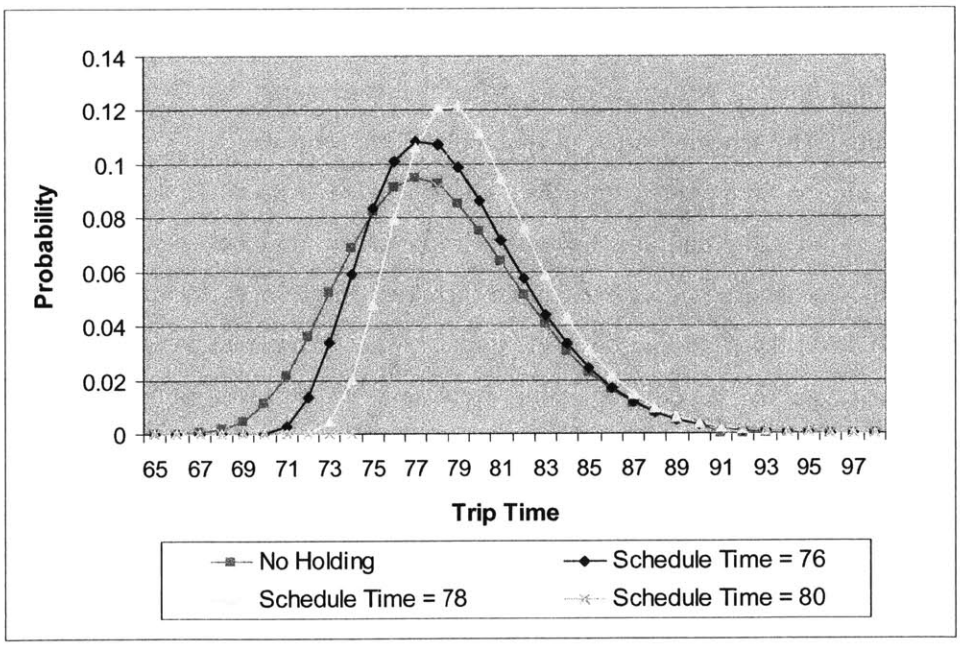


Figure 3-4 Trip Time Distribution with Different Schedule Trip Times

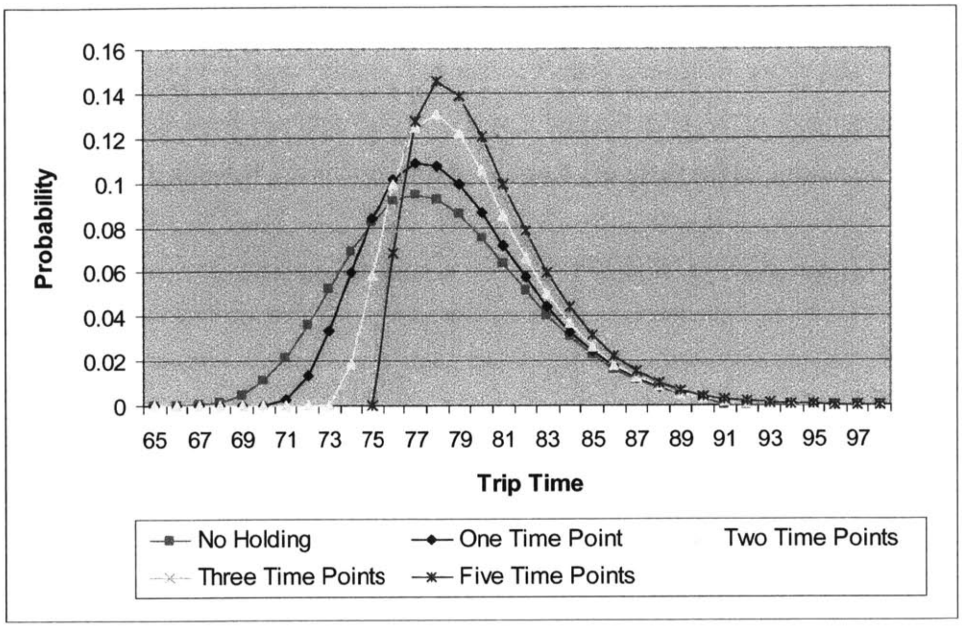


Figure 3-5 Trip Time Distribution with Different Number of Time Points

Figure 3-4 shows the trip time distributions with different scheduled departure times at time point 3 when holding is implemented at just that time point, which is located at the mid-point of the route. The schedule times at time point 3 are set to the 50, 75 and 85 percentile on the cumulative time to time point 3 function. The scheduled times at the ending terminal are the scheduled time at the mid-point plus the average segment trip time between time point 3 and the ending terminal. As the scheduled trip time increases from 76 to 80 minutes, the trip time distribution moves to the right and becomes tighter. This means that as expected the expected trip time increases and the standard deviation decreases with increasing scheduled times. Figure 3-5 shows the trip time distributions when holding is implemented at a different number of time points. The scheduled time for each segment is set to the 50 percentile of the cumulative segment time in the unconstrained segment time distribution. As the number of time points increases, the trip time distribution moves to the right and becomes tighter just as when the scheduled departure time increased. This also shows that the expected trip time increases and the standard deviation decreases with the number of time points.

The reduced deviation with increases in schedule time and the number of time points can improve schedule adherence at the time points along the route. However, as the trip time distribution shifts to the right, the expected trip time also increases, and thus in-vehicle time increases. Here, it is understood that the schedule time and the number of time points determines the schedule adherence at the time points including the ending terminal and the expected passenger in-vehicle time.

The other interesting issue raised by Figure 3-5 is the influence of the location and the schedule time of the last time point on the trip time distribution. Comparing the distributions of three time points and five time points, the two trip time distributions overlap each other. Two cases have the last time point at time point 5 with schedule times there of 65 minutes, which is 50 percentile of cumulative time to time point 5. This shows that the location of the last time point almost totally determines the shape of the trip time distribution. In order to investigate the impact of time point location further, Figure 3-6 is generated. It shows that the trip time distributions are almost the same regardless of the number of time points when the last time point is point 5 and the schedule times at that time point are the same. From this observation, we can say that the critical decisions that affect the trip time distribution are the location of the last time point and the scheduled time at that point.

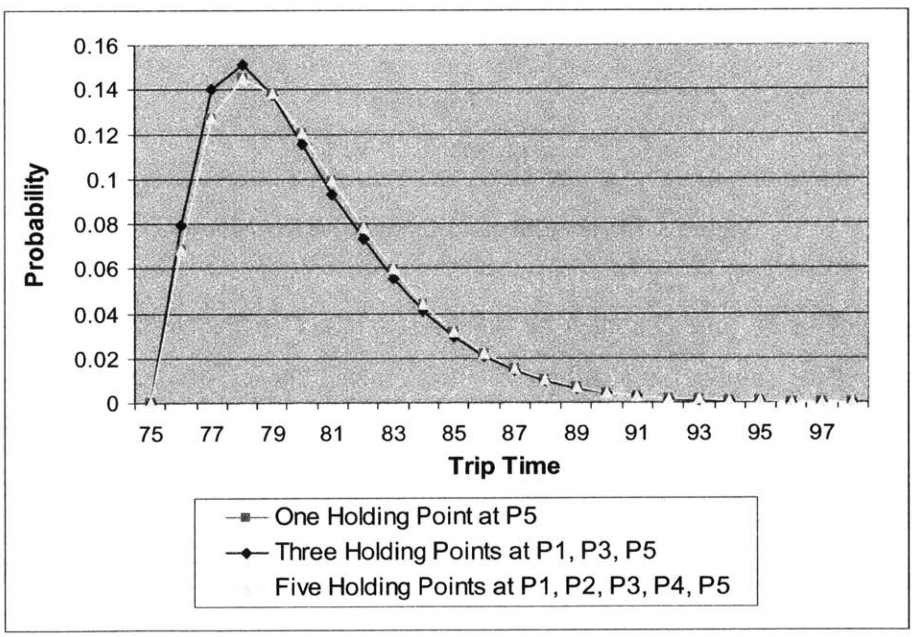


Figure 3-6 Influence of the Location and Schedule Time of the Last Time Point

3.2.2. Setting Cycle Time and Recovery Time

After estimating the trip time distribution based on the scheduled trip time, we can decide the half cycle time depending on the desired on-time departure probability at the terminal. The recovery time is then simply the difference between the half cycle time and the schedule time. When the scheduled trip time is 80 minutes (see Figure 3-4), Figure 3-7 shows the probability density function and cumulative distribution of trip time.

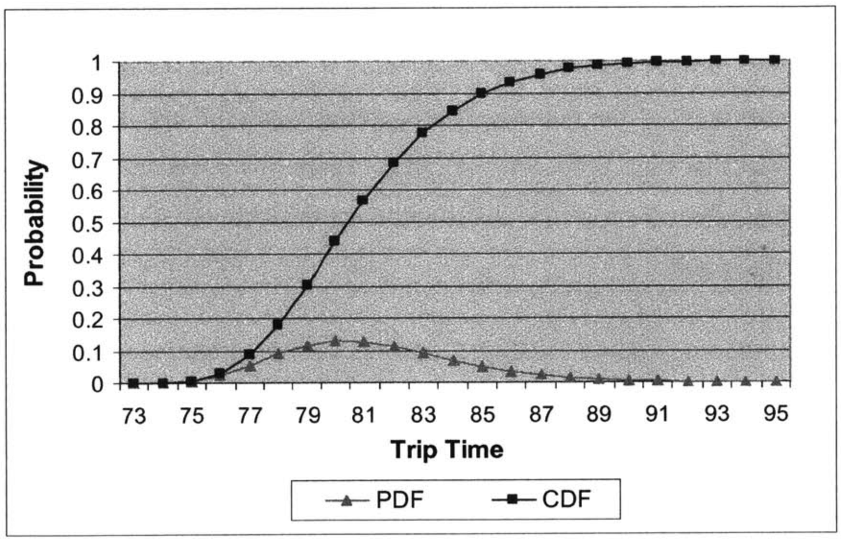


Figure 3-7 Probability and Cumulative Distributions

The half cycle time can then be determined based on the desired on-time departure probability from the cumulative distribution. If the transit agency wants the on-time departure probability at the terminal to be 90%, the half cycle time needs to be set at 86 minutes from the cumulative trip time distribution, and the recovery time is set to 6 minutes as a result. If the on time departure probability is increased to 95%, then the half cycle time will be 88 minutes and recovery time will be 8 minutes. The cumulative probability of trip times is shown in Table 3-2.

Half Cycle Time	Cumulative Probability
80	0.43
81	0.55
82	0.67
83	0.76
84	0.83
85	0.88
86	0.91
87	0.94
88	0.95
89	0.96

Table 3-2 Cumulative Probability of Trip Times

3.2.3. Dwell Time

In this analysis, the vehicle trip time is split into vehicle movement time and dwell time. The dwell time is the time spent while passengers are boarding or alighting at bus stops and the vehicle movement time is the trip time excluding dwell time. The vehicle movement time will be affected by traffic conditions, including traffic congestion and signalized intersections. The traffic conditions change over the course of the day. So, during the AM and PM peak when there is higher traffic volume on the route, the movement time will have a higher mean and standard deviation due to greater uncertainty. The vehicle movement time is also indirectly affected by the headway. As headway changes the passenger demand on the route will be affected and it should change the number of stops at which the vehicle actually stops for passengers to board and alight. If the headway increases, the vehicle will have to stop more frequently to handle the increased number of passengers. This will result in more accelerations and decelerations, and thus increase the vehicle movement time. In this research, the acceleration and deceleration time is assumed to be small enough not to affect the movement time.

However, the dwell time will be mainly affected by the schedule parameter, headway. If there is high passenger demand due to longer headways, we need more time for passengers to board and alight at bus stops. The dwell time can be expressed as a function of the number of passengers boarding and alighting. If the number of passengers boarding and alighting at a stop are known, we can derive a dwell time model at the stop level. First of all, with the assumptions that the boarding and alighting rates are constant, and there is no interference between passengers boarding and alighting and with passengers already on board, we can apply a simple linear model:

$$D_{ij} \text{ (Dwell Time at bus stop } j\text{, trip } i) = w + \beta_1 * A_{ij} + \beta_2 * B_{ij} \tag{3-14}$$

where

w = *door opening and closing time*

A_{ij} = *number of passengers alighting at stop j, trip i,*

B_{ij} = *number of passengers boarding at stop j, trip i,*

β_1, β_2 = *estimated parameters.*

This model is valid when the entire boarding and alighting processes occur through a single door. In the case that alighting passengers can also use the rear door, the coefficient of A_{ij} will be reduced.

If there is friction with passengers on board, the boarding and alighting rates will decrease as the number of passengers on board increase. However, the number of passengers on board would not affect the dwell time linearly. For example, there would not be substantial difference between having 10 passengers and 15 passengers in the bus. Therefore, there should be a critical load level beyond which dwell time begins to be affected due to passenger friction and the passenger friction term will influence the dwell time only when the passenger load exceeds this critical level. Above the critical level, the dwell time is affected by both the number of passengers on board and the number of boarding and alighting passengers. Therefore, the friction term can be expressed as a product of the number of boarding and alighting passengers and the number of passengers on board beyond the critical load level. Considering the passenger friction term, the dwell time model is as follows:

$$D_{ij} \text{ (Dwell Time at bus stop } j\text{, trip } i) = w + \beta_1 * A_{ij} + \beta_2 * B_{ij} + \beta_3 * \begin{cases} (A_{ij}+B_{ij})*(N_{ij}-N_c), & \text{if } N_{ij} \geq N_c \\ 0, & \text{if } N_{ij} < N_c \end{cases} \tag{3-15}$$

where

N_{ij} = *number of passenger on board at stop j, trip i,*

N_c = *critical threshold for passenger congestion*

β_1, β_2, β_3 = *estimated parameters*

This is just one possible friction term, which is linear in (N_{ij}-N_c). Other forms of friction term which maybe non-linear in (N_{ij}-N_c) can also be tested.

The dwell time model at the stop level can be estimated only if there is information about passengers boarding and alighting at each stop. However, in reality, collecting data on the passengers boarding and alighting is time consuming and expensive. If we only have trip level data on the total number of passengers boarding at all stops, which is much more plausible, we can derive a dwell time model at the aggregate trip level.

The principal variable, which should affect the trip level dwell time will be the number of passengers boarding. With the assumption that the vehicle stops at all bus stops, the trip level dwell time can be expressed as follows:

$$D_i \text{ (Aggregate Dwell Time for trip } i) = kw + \beta_4 * f(L_i) \tag{3-16}$$

where

k= number of stops on the route

w = door opening and closing time

L_i = total number of passengers boarding on trip i

β_4 = estimated parameter.

Here, the relationship between total number of passengers boarding and dwell time is not determined. It is expressed as a general function of the total number of passengers boarding. Different routes would have different functional forms of passenger demand according to the route characteristics, and thus the functional form that represents the relationship between the total number of passengers boarding and dwell time should be selected by testing different functional forms.

However, the number of stops that a vehicle actually stops at depends on the total number of passengers boarding. If there is low passenger demand on bus i, the bus will skip some bus stops where there are no passengers boarding or alighting. Therefore, the sum of door opening and closing time for a trip can also be a function of total passenger demand. There may be a critical passenger demand level beyond which the vehicle cannot skip any stops (there will be at least one passengers boarding or alighting for all stops). If the passenger demand exceeds the critical demand level, the door opening and closing time will have a constant value, kw. Thus, the equation below can be used for the door opening and closing time in the dwell time of a trip.

$$\sum_{j=1}^{k} \mathrm{w} = \begin{cases} kw, \ if\ L_i \geq L_c \\ \beta_5 * Li, \ if\ L_i < L_c \end{cases} \tag{3-17}$$

where Lc is the critical passenger demand level for the door opening and closing time term and β_5 is an estimated parameter.

Now, the dwell time at the trip level can be expressed as:

$$Di\ (Dwell\ Time\ of\ trip\ i) = \begin{cases} kw, \ if\ L_i \geq L_c \\ \beta_5 * Li, \ if\ L_i < L_c \end{cases} + \beta_4 * f(L_i) \tag{3-18}$$

As with the stop level dwell time model, if there is friction between passengers, the passenger demand will have greater influence as the total passenger demand on the route increases. Also, there will be a critical total passenger demand level beyond which the dwell time is increased significantly. Considering the friction term, the following model might apply:

$$Di\ (Dwell\ Time\ of\ trip\ i) = \begin{cases} kw, \ if\ L_i \geq L_c \\ \beta_5 * Li, \ if\ L_i < L_c \end{cases} + \beta_4 * f(Li) + \beta_6 * \begin{cases} L_i*(L_i - L_c'), \ if\ L_i \geq L_c' \\ 0. \ if\ L_i < L_c' \end{cases} \tag{3-19}$$

where Lc' is the critical passenger demand level for the passenger friction term, and β_4, β_5 and β_6 are estimated parameters.

The dwell time models at the stop level can be expressed as a function of the number of passengers boarding and alighting and the dwell time models at the trip level can be expressed as a function of total passengers boarding. The passenger demand on the bus can be expressed as a function of headway. With the assumption that passengers arrive randomly the passenger arrival rate is constant over the time period and known, the expected number of passengers for any trip i should be:

$$Li = l_q * h_q \tag{3-20}$$

where l_q is the passenger arrival rate during time period q (passenger/minute) and h_q is the headway during time period q.

In the above equation, we can easily understand that total passenger boardings per bus also increases as the vehicle headway is increased since the same demand is distributed over fewer buses. For example, if the total demand on the route during the AM peak period (from 6 to 8AM) is 1000, and if vehicle headway is increased from 10 to 15 minutes, the expected number of passengers per bus will increase from 84 passengers/bus to 125 passengers/bus. This assumes that the passenger demand does not decrease as a result of the reduced service frequency. Thus, vehicle headway determines passenger demand per bus. Also the variance is the same as the mean since the number of passengers that arrive between headway follows Poisson distribution with the assumption of random arrival. Therefore, the variance of the number of passengers per trip increases as headway increases though the passenger arrival rate is constant.

As shown above, the dwell time can be expressed at the stop level as a function of the number of passengers boarding and alighting or at the trip level as a function of the total number of passengers boarding. The number of passengers boarding at a stop and the total passenger demand on a bus are both a function of headway. Therefore, the headway is expected to influence the dwell time. As the headway increases, passenger movements at bus stops increase, which require longer dwell time. Moreover, as the headway increases, the variance in the passenger demand increases and thus the variance of dwell time also increases as well as the mean of dwell time. Since dwell time is a part of vehicle trip time, the trip time distribution will change with the headway.

3.3. Relationships between Schedule Parameters

The change of one schedule parameter affects the other parameters as well as the trip time distribution. Based on the relationship between the trip time distribution and schedule parameters discussed in section 3.3, the secondary impacts of change of schedule parameters, the relationships between schedule parameters, will be discussed in this section.

3.3.1. Schedule Time and Recovery Time

As described in section 3.2.2, the recovery time is determined by the trip time distribution and the desired on time departure probability at the terminal. If the transit agency wants 90 percent of vehicles to be able to start their next trip on time, the half cycle time is determined as 90th percentile of the cumulative trip time function, and consequently, the recovery time is set to the difference between scheduled time and half cycle time. In that section, I showed the effect of on-time departure probability on the recovery time. In this section, I show how the recovery time will change with the scheduled time on the route.

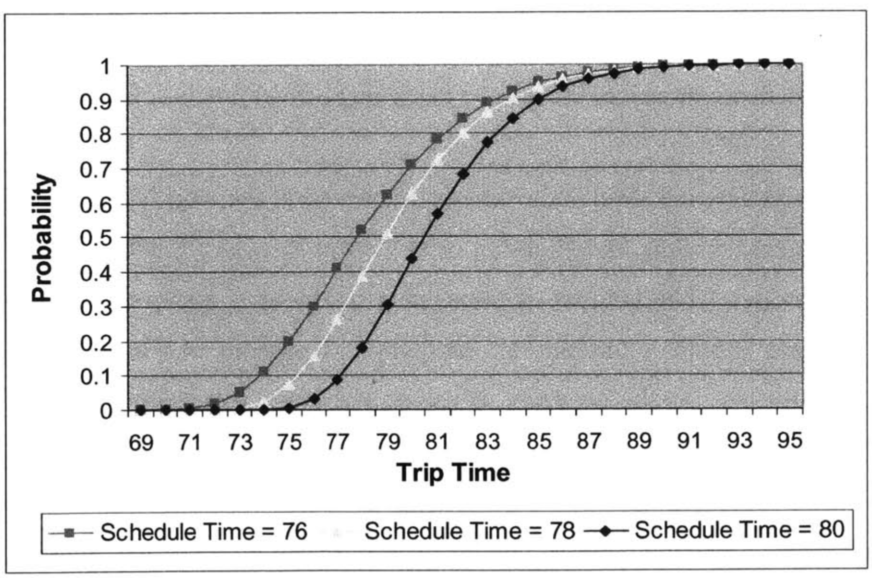


Figure 3-8 Cumulative Distribution with Different Schedule Times

Different schedule times will yield different trip time distributions. Therefore, the recovery time depends on the schedule time. Figure 3-8 shows the cumulative distributions of the trip time with different scheduled trip times of 76, 78, and 80 minutes respectively when holding is implemented at just the route mid-point. The cumulative probability of trip times with different scheduled trip times are listed in Table 3-3. From this example, I will show how different schedule times and on-time probabilities affect the recovery time.

	Cumulative Probability		
Trip Time	Scheduled Trip Time = 76	Scheduled Trip Time = 78	Scheduled Trip Time = 80
80	0.711	0.626	0.437
81	0.785	0.723	0.566
82	0.843	0.801	0.681
83	0.889	0.861	0.774
84	0.923	0.905	0.845
85	0.947	0.936	0.897
86	0.965	0.958	0.934
87	0.977	0.973	0.958
88	0.985	0.983	0.974
89	0.991	0.989	0.984
90	0.994	0.993	0.991
91	0.996	0.996	0.994

Table 3-3 Probability of Trip Times with Different Scheduled Trip Times

First of all, this example shows that the different desired on-time departure probabilities at the terminal yield different recovery times. From the trip time distribution for a 76 minute scheduled trip time, the half cycle times are set to 82 minutes, when the on time departure probability is 85%, and 85 minutes when it is 95%. From the trip time distribution for an 78 minute scheduled trip time, the half cycle times are set to 83 minutes when the on time departure probability is 85% and 86 minutes when it is 95%. From the trip time distribution for an 80 minute scheduled trip time, the half cycle times are set to 84 minutes, when the on time departure probability is 85%, and 87 minutes when it is 95%. Therefore, the on-time departure probability affects setting the half cycle time and also the recovery time, which is the difference between the half cycle time and the schedule time.

Also, it is clear that different scheduled times yield different recovery time. Given the on time departure probability as 95%, the different trip time distributions with scheduled trip times of 76, 78, and 80 minutes have half cycle times of 85, 86 and 87 minutes respectively according to Table 3-3. Thus the recovery times are 9, 8 and 7 minutes respectively; as the schedule time increases, the recovery time necessary to maintain the same on time probability decreases.

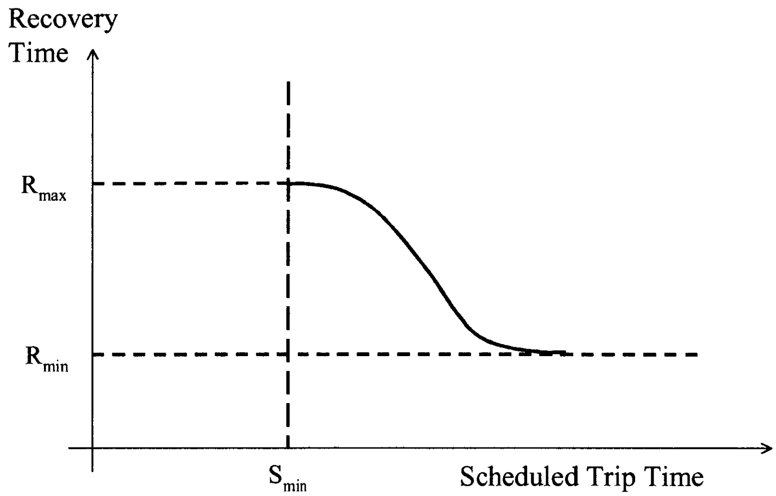


Figure 3-9 Relationship between Scheduled Trip Time and Recovery Time

Figure 3-9 shows the relationship between scheduled time and recovery time with a given on time departure probability at the terminal. The minimum schedule time is the minimum travel time when there is no holding. Since almost every trip arrives late at the terminal with minimum schedule time, S_{min}, we have the maximum recovery time, R_{max}. As the schedule time increases, on-time arrivals at the terminal increase, and thus the necessary recovery time decreases. After the scheduled trip time reaches a certain point at which almost every trip can arrive at the terminal on time, the recovery time will remain the same; the minimum recovery time, R_{min}. In this case, recovery time is just used for the driver's break, not for catching up with the schedule.

The probability that a vehicle starts its next trip on time depends on the trip time distribution, which is a function of the schedule time and it determines where to set the recovery time. Recovery time is necessary to reduce the probability of late departure at the terminal as well as to provide a break to drivers, therefore, it is important to set recovery time based on understanding the probability that vehicles can start their next trip on time and the relationship between the scheduled time and recovery time.

3.3.2. Recovery Time and Vehicle Headway

Increasing the vehicle headway increases both dwell time and uncertainty in trip time, which causes increases of average trip time as well as variability of trip time. Since the recovery time is based on the trip time distribution and the headway can affect the trip time distribution, the vehicle headway indirectly affects the recovery time.

The recovery time also affects the evenness of vehicle headways. By having a certain recovery time at the terminal, we can control the departure time at the terminal, and thus the headway variability. For example, when the recovery time is k minutes, trips, which arrive at the terminal before the scheduled trip time plus recovery time, the half cycle time, can make the next trip on time. Therefore, as the recovery time is increased, more vehicles can start the next trip on time and departure headway variance at the terminal will be reduced. If the vehicle arrives later than the half cycle time, the departure time for the next trip will be the arrival time at the terminal or the sum of the scheduled departure time and the difference between schedule time and vehicle arrival time. Therefore, the trip start time can be expressed as follows:

$$S = \begin{cases} S_0 \ , \ if\, T_{ap} < C \\ T_{ap} \ , \ if\, T_{ap} \geq C \end{cases} \tag{3-21}$$

where S is the actual departure time, S_0 is the vehicle scheduled departure time at the terminal and T_{ap} is the vehicle arrival time of the previous trip. The probability density function of departure time at the terminal, S, can be derived as follows:

$$F_S(s) = P\{S \leq s\} = P\{T_{ap} \leq t_{ap}\} = F_{T_{ap}}(t_{ap}) \qquad T_{ap} \geq C \tag{3-22}$$

and thus

$$f_S(s) = F_S^{'}(s) = f_{T_{ap}}(t_{ap}) \qquad T_{ap} \geq C \tag{3-23}$$

Since the vehicle cannot start its next trip before the half cycle time, the probability distribution of S has a discrete mass at S_0.

$$P\{S = s_0\} = P\{T_{ap} \leq C\} = F_{T_{ap}}(C) \qquad T_{ap} < C \tag{3-24}$$

Therefore, the probability distribution of vehicle departure time at the starting terminal has a spike at S_0 and the distribution remains the same as the distribution of arrival time at the ending terminal of previous trip, T_{ap}, when $T_{ap} \geq C$.

The departure headway distribution at the starting terminal can be derived from the departure time distribution at the starting terminal with an assumption that if a trip is late the previous and next trips are on time. If a vehicle departs the terminal late, the departure headway of this trip and the next trip will be affected. A trip, which departs the starting terminal t minutes late, will cause t minutes longer headway for this trip and t minutes shorter headway for the next trip. Therefore, the departure headway distribution remains the same as the arrival time distribution of the previous trip when the actual headway is greater than the scheduled headway. Also, the departure headway distribution when the actual headway is smaller than the scheduled headway will be the symmetrical distribution of the arrival time distribution of the previous trip. The probability that the vehicle headway is longer than the scheduled headway will be the same as the probability that the vehicle departs the terminal late. Since one late trip causes one long headway and one short headway, the probability that a departure headway is shorter than the scheduled headway will be the same as the probability that a headway is longer than the scheduled headway. Therefore, the departure headway distribution has a discrete mass at the scheduled headway and it has the same distribution with the arrival time distribution of previous trip when the actual headway is greater than or smaller than the scheduled headway. Therefore, if the half cycle time (i.e. recovery time) increases, the probability that a vehicle can depart on time increases and the variability of the departure time at the starting terminal decreases and thus the departure headway distribution also has smaller variability.

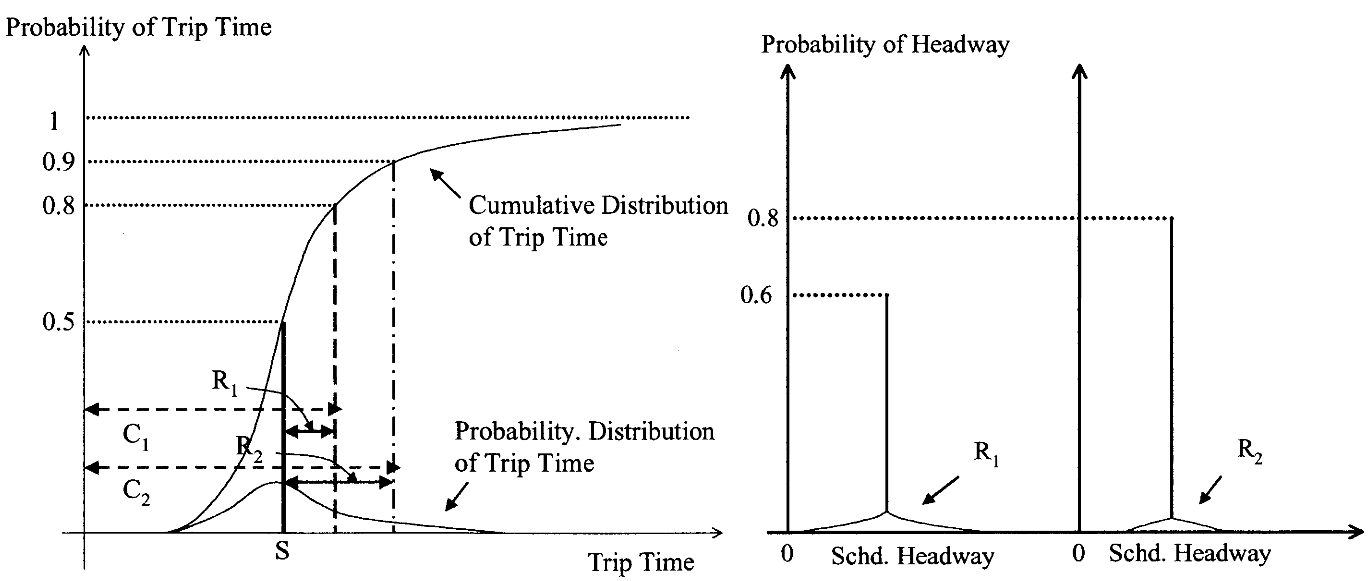


Figure 3-10 Departure Headway Distribution at Terminal with Different Recovery Times

Figure 3-10 shows the headway distribution at the terminal with different recovery times (different half cycle times). If the agency wants to achieve a higher on-time departure probability, it will have to increase the scheduled recovery time. In Figure 3-10, if the desired on-time departure probability is increased from 80% to 90%, the recovery time must be increased from R_1 to R_2. When the recovery time is R_1, 80% of trips can start on time and 20% of trips cannot. This will cause 20% of departure headways to be longer than scheduled and 20% to be shorter than scheduled. In case of R_2, 10% of trips cannot depart the terminal on time and it will cause 10% long departure headways and 10% short departure headways. Therefore, the probability that the scheduled headway is achieved will be 60% and 80% respectively and thus the headway variability with recovery time R_2 will be smaller than that with R_1. Therefore, the recovery time determines the departure headway distribution at the terminal.

3.4. Operational Cost and Schedule Parameters

Operational cost is divided into two parts: the scheduled cost and the expected cost of late trips. In this section, I will derive a cost model, which incorporates those two types of costs and the relationships that can be obtained from the cost model.

3.4.1. Cost Model

The scheduled cost includes the driver wage, which is related to the number of vehicle hours, and fuel cost and maintenance cost, which are related to the vehicle miles. The cost for one trip can be expressed as follows:

$$\text{Scheduled Cost} = 2(C_h * C + C_m * d) \qquad (3\text{-}25)$$

Where

C: the half cycle time

d: the route length

C_h*: the unit cost associated with vehicle hours*

C_m*: the unit cost associated with vehicle miles*

The scheduled cost during a time period can be calculated by multiplying this by the number of trips during the period.

The expected cost of late trips depends on the total time of pieces of work compared with the scheduled work time. The unit cost associated with late trips, C_a, is due to the operator overtime wage. This cost will be generated only if the operator has to work overtime, that is the total work time is greater than the scheduled work time. Each piece of work will include a different number of trips. The total work time can be expressed in general as:

$$\textit{Total Time for a piece of work } j,\ T_j = \sum_{i=1}^{k} R_i * X_{ij} \tag{3-26}$$

where

T_i: Time for trip i,

C: Half Cycle Time

R_i: T_i, if travel time is greater than C or C, otherwise

X_{ij}: 1, if trip i is included in piece of work j or 0, otherwise

For each piece of work j, we can generate the total work time distribution, f_j. When the driver's work time is W_j, the probability that driver will work overtime will be $\int_{W_j}^{\infty} f_j$, and the expected overtime will be $\int_{W_j}^{\infty} (T_j - W_j) f_j$. Therefore, we can express the expected cost of lateness for a piece of work j as:

$$\textit{Expected cost of late trip for a piece of work } j = C_a \int_{W_j}^{\infty} (T_j - W_j) f_j \tag{3-27}$$

The expected cost of lateness during a day can be calculated by summing up the expected cost of late trip for each trip. If we know that the number of pieces of work for one day is k, the total late trip cost for one day will be:

$$\textit{Total late trip cost for a day} = C_a \sum_{j=1}^{k} \int_{W_j}^{\infty} (T_j - W_j) f_j \tag{3-28}$$

In my research, first of all, I will estimate the scheduled cost for each time period having homogeneous trip times, that is, having the same trip time distribution, f_i. Then the expected cost of late trips per day will be estimated. After estimating the scheduled cost and late trip cost separately, the overall cost needed over a day will be estimated by summing the two costs.

3.4.2. Operational Cost and Cycle Time

The scheduled cost over a time period p can be expressed as a function of headway, cycle time and route distance as:

$$Scheduled\ Cost = [C_h * C + C_m * d] * (p/h) * 2 \quad (3\text{-}29)$$

When the headway is given, the scheduled cost depends on the cycle time. The expected cost for late trip over a day will be as derived in the previous section.

$$Total\ late\ trip\ cost\ for\ a\ day = C_a \sum_{j=1}^{k} \int_{W_j}^{\infty} (T_j - W_j) f_j \quad (3\text{-}30)$$

The late trip costs will vary depending on C_a, the driver's work time and total time distribution for each piece of work. Since the scheduled cost is estimated based on the time period and late trip cost is based on the day, we have to estimate the scheduled cost per day to integrate those two costs. Let's say there are l time periods in a day and a time period q has cycle time, C_q, time duration, p_q, and headway, h_q. The scheduled cost per day can be calculated by summing the scheduled costs for each time period:

$$Scheduled\ Cost\ for\ a\ day = \sum_{q=1}^{l} [C_h * C_q + C_m * d] * (p_q / h_q) * 2 \quad (3\text{-}31)$$

Therefore, overall operational cost per day is estimated by summing the two costs:

$$Operational\ Cost\ per\ day = \sum_{q=1}^{l} [C_h * C_q + C_m * d] * (p_q / h_q) * 2 + C_a \sum_{j=1}^{k} \int_{W_j}^{\infty} (T_j - W_j) f_j \quad (3\text{-}32)$$

Thus, the scheduled cost component will increase as the scheduled time increases, while the late trip cost component, $C_a \sum_{j=1}^{k} \int_{W_j}^{\infty} (T_j - W_j) f_j$, will decrease since the probability that the total time will exceed the driver's work time will decrease. Therefore, there is a trade off between the scheduled cost and the late trip cost and we can find the optimal scheduled trip time that minimizes the operational cost with a given headway.

3.4.3. Operational Cost and Vehicle Headway

According to the scheduled cost component in equation 3-31, the operational cost will decrease as the headway increases since the number of trips during p_q will decrease. Change of headway will also influence the trip time distribution, f_j, by changing the dwell time. If the headway increases, the trip time will increase due to longer dwell time, and thus the probability of late departures will increase. Accordingly, the probability that the total time will exceed the driver's work time will increase with increasing headway, given the cycle time. Therefore, the late trip cost, $C_a \sum_{j=1}^{k} \int_{W_j}^{\infty} (T_j - W_j) f_j$, will increase when the headway increases.

3.4.4. Vehicle Headway and Cycle Time

The operational cost over a day depends on the number of trips required during the day and the cycle time for each time period as shown in Equation 3-31.

There is a tradeoff between vehicle headway and cycle time when the operational cost is given. As shown in the above equation, for the same cost we could either increase the cycle time and reduce frequency, or decrease the cycle time and provide more frequent service. However, if we increase cycle time, the additional cost caused by late trips, would decrease since the probability that total travel time exceeds the driver's work time will decrease due to more slack time and recovery time. Therefore the operator needs to choose an optimal combination of frequency and cycle time by understanding how the frequency and cycle time affect the operational cost and the tradeoffs between them.

3.5. Service Quality and Schedule Parameters

There are several possible measures for evaluating service quality. In this thesis, I measure service quality in terms of trip speed, reliability, and crowding. Passenger in-vehicle time reflects the speed of the service, passenger waiting time and schedule adherence reflect the reliability of the service, and crowding reflects the comfort of the service. This section addresses service quality and derives the relationships between service quality and the schedule parameters.

3.5.1. Passenger In-vehicle Time

Passengers typically spend more than half their trip time in the bus, and so passengers have a clear interest in reducing in-vehicle time. If we assume that the vehicle speed is constant along the route, passenger in-vehicle time can be measured as:

$$\textit{In-vehicle time} = E(t) * \frac{\bar{l}}{d}$$

where E(t) is expected trip time of the route, $\bar{l}$ is the average passenger trip length on the route, and d is the route distance. Thus, as expected passenger in-vehicle time depends on the trip time distribution, which determines the expected trip time.

The trip time distribution is affected by the scheduled time and headway. If the scheduled trip time increases, the expected trip time increases and the probability of a late trip also increases. When the headway increases, the dwell time increases since the same demand is distributed over fewer vehicles, and thus expected trip time increases.

3.5.2. Passenger Waiting Time

Passengers react more negatively to waiting time than in-vehicle time since waiting time tends to be more uncertain and less comfortable. For this reason, usually, one minute of passenger waiting time is valued the same as 1.5 minute of in-vehicle time. With the assumption that all passengers can board the first bus to arrive, the expected passenger waiting time at a stop, E(w), for passengers who arrive randomly is:

$$E(w) = \frac{H}{2} + \frac{V(h)}{2H}$$

where H is the average departure headway and V(h) is the variance of the departure headway at the stop.

Considering just a single time point first, the departure headway distribution at the time point determines the passenger waiting time.

$$E(T_{d1}) = \int_{S_1}^{\infty} t f_{T_{a1}}(t)dt + S_1 *(1- \int_{S_1}^{\infty} f_{T_{a1}}(t)dt) \quad (3\text{-}4)$$

$$D^2(T_{d1}) = \int_{S_1}^{\infty} t^2 f_{T_{a1}}(t)dt + S_1^2(1 - \int_{S_1}^{\infty} f_{T_{a1}}(t)dt) - \{E(T_{d1})\}^2 \quad (3\text{-}5)$$

According to Equations 3-4 and 3-5 in Section 3.3.1, the departure time distribution depends on the trip time distribution and schedule time. If the schedule time increases, the average departure time increases while the variance of departure time decreases. Since the trip time distribution is affected by the scheduled headway and the trip time distribution influences the average and variance of actual departure time, the scheduled headway also has an influence on the passenger waiting time. When the half cycle time is fixed, an increase in scheduled headway will cause a decrease in on time departure probability by moving the trip time distribution to the right. Therefore, an increase of headway will increase the departure headway variance as well as the average headway, and thus the average passenger waiting time will also increase. As shown in the relationship between headway and recovery time, the recovery time determines the departure headway distribution by controlling the on time departure probability at the terminal. An increase of recovery time will decrease headway variance since it means more vehicles can start next trip on time, and thus decrease waiting time when scheduled headway and schedule trip time are fixed. Therefore, passenger waiting time is affected by vehicle headway and recovery time.

3.5.3. Schedule Adherence

Transit agencies usually use schedule adherence for evaluating their service performance and try to improve schedule adherence to provide better service. Schedule adherence can be measured by the average deviation from schedule at the origin and destination terminals, and at intermediate time points. Schedule adherence at the origin is simply the on time departure probability at the starting terminal. Therefore, schedule adherence at the origin is affected by the recovery time. As a vehicle moves along the route, the probability that the vehicle is late will increase since there is more uncertainty and less slack time to catch up with schedule. Thus, schedule adherence at the destination will be the worse than that at the intermediate time points. Therefore, schedule adherence at the destination can represent the worst case for schedule adherence at the time points. Schedule adherence at the destination depends on the on time arrival probability at the ending terminal. Here it is assumed that a vehicle is "on time" if it is no more than 5 minutes later than the schedule time. Since the on time arrival probability is determined by the schedule time, schedule adherence at the destination is affected by the schedule time. In summary, schedule adherence is determined by on time departure probability at the starting terminal and on time arrival probability at the ending terminal, and thus it is affected by the recovery time and the schedule time.

3.5.4. Crowding

Crowding can be measured by the ratio of standees to seated passengers. Since the headway determines the passenger load it is the most important scheduling parameter in determining the crowding levels on the vehicles. There is a certain crowding level beyond which overall operation performance can deteriorate significantly due to extended dwell times. Therefore, most transit agencies have maximum acceptable levels of crowding and determine the minimum vehicle frequency to avoid serious vehicle overcrowding. Recovery time is also important in controlling crowding levels. Even if average passenger demand is not too high, if vehicle headways are not even, crowding levels on individual vehicles can still reach the critical point. Therefore, it is important to maintain even vehicle headways. By having enough recovery time, the vehicle dispatching times can be met more reliably, and thus vehicle headways and crowding levels can be better controlled.

3.6. A Proposed Scheduling Process

As discussed in Chapter 2, with the traditional scheduling process, we cannot easily assess different combinations of schedule parameters while recognizing the relationships between schedule parameters, operational cost and service quality. Rather the schedule parameters are largely based on the service standards and policies. In an improved scheduling process, the step of exploring different combinations of schedule parameters and evaluating their associated operational cost and service quality should be included to find combinations which better satisfy the agency's objectives. This process should also include the inter-relationships and secondary impacts described above. The process should include operational cost estimation, passenger level of service estimation, frequency setting, scheduled time setting, and necessary recovery time setting. Schedule parameters will be determined to meet the operator's objectives, which requires tradeoffs between operational cost and passenger level of service. Here, I assume that the number and location of time points are already decided based on the passenger demand information and the route location, and thus this process mainly deals with setting the schedule parameters; frequency, schedule time, and recovery time.

The process including the assessment of different schedule parameters is:

1. Develop an upper bound on headway based on the maximum crowding standard and a lower bound on headway based on Revenue/Cost ratio or Benefit/Cost ratio.
2. Service frequency setting: According to the current general service standards, the initial frequency of the route will be chosen.
3. Minimum schedule time setting: The minimum schedule time at the last time point will be set to the schedule time which makes 20% of trips early at that time point. The schedule time for the last segment (from the last time point to the destination) is the average segment trip time. Thus, the minimum schedule time will be the sum of the minimum schedule time at the last time point and the average last segment trip time.
4. Trip time distribution estimation: The trip time distribution with the given service frequency (see step 2) and the minimum scheduled time (see step 3) will be estimated.
5. Half cycle time setting: The half cycle time necessary to achieve 85%, 90%, 95%, and 97% on time departure probabilities will be estimated from the cumulative trip time distribution. The recovery time is then set to the difference between the half cycle time and schedule time in this step of the process.

6. Operational cost and service quality estimation: Estimate the operational cost and service quality for the given combination of headway, schedule time, and half cycle time.
7. Schedule time change: Increase the schedule time and repeat steps 4 to 6 of the process until 80% of trips can arrive earlier than the schedule time.
8. Service frequency change: Increase or decrease the service frequency and repeat steps 3 to 7 of the process until it reaches the upper bound and lower bound on headway.
9. Tradeoffs between the operational cost and service quality: Plot the operational costs and service qualities with different combinations of service frequency, scheduled time and recovery time.

In the above process, first of all, the upper bound on headway is determined based on the maximum acceptable level of crowding and the lower bound on headway is determined based on the Revenue/Cost ratio or Benefit/Cost ratio. Once the upper and lower bounds on headway are determined, initial frequency and schedule trip time are set. The minimum schedule time at the last time point is set to the schedule time which makes 20% of trips early at that time point since below the minimum schedule time, the trip time distribution does not change significantly and thus the operational cost remains the same with just deteriorating overall service quality. Given the service frequency and minimum schedule time, the half cycle time is selected based on the on time departure probability at the terminal. The operational cost and service quality will change with the half cycle time, and hence the recovery time. The operational cost and service quality should be estimated based on the relationship between operational cost and cycle time and the relationship between service quality and recovery time.

After that, given the service frequency, the schedule time is increased in order to improve on-time arrival probability at time points. The schedule time is increased until 80% of trips can arrive earlier than the schedule time and thus on time arrival probability with a 0-5 minutes window will be about 99%. According to the increase of schedule time, the trip time distribution will change, i.e. average trip time increases and variance of trip time decreases. Therefore, the trip time distribution with increased schedule time should be estimated based on the relationship between schedule time and trip time distribution. Given the service frequency, schedule time, and estimated trip time distribution, the half cycle time is changed according to the desired on time departure probability at the terminal. The operational cost and service quality will change due to increase in schedule time and half cycle time (i.e. increase of recovery time) and the new operational cost and service quality will be estimated.

Next, the impacts of service frequency change will estimated. According to the service frequency change, the passenger demand on the bus will change, and thus the dwell time, which is a function of passenger demand, will be affected. Moreover, the trip time distribution will be affected. Therefore, the trip time distribution with changed service frequency should be estimated based on the relationship between frequency and passenger demand and the relationship between passenger demand and dwell time. Given the frequency, the minimum schedule time, and the estimated trip time distribution, the half cycle time is changed according to the desired on time departure probability at the terminal. After this, the same process, increasing the schedule time, estimating trip time distribution with increased schedule time, changing half cycle time, and estimating the operational cost and service quality with different combination of schedule parameters, is repeated. Finally, the tradeoffs between operational cost and service quality can be shown by plotting the operational costs and service qualities for different combinations of service frequency, scheduled trip time and recovery time.

In the process described above, the different combinations of schedule parameters can be explored and the operational cost and service quality of those combinations estimated. However, without a thorough understanding of the impact of changing the schedule parameters, the operational cost and service quality cannot be estimated accurately. It is certain that changing the schedule parameter will change the operational cost and service quality since they are functions of the schedule parameters. However, the secondary impacts of schedule parameters change are likely to be ignored. As explained earlier, change of schedule parameters will change the trip time distribution and it will furthermore influence the decision on other schedule parameters. Therefore, the operational cost and service quality estimations should be performed recognizing the relationships between schedule parameters.

After estimating the operational cost and service quality of different combinations of schedule parameters based on the relationships between schedule parameters, operational cost, and service quality, the schedule parameters, which best satisfy the transit agency's objectives, can be selected. Since the schedule parameters are decided to meet the transit agency's objectives, the decision makers should fully understand the relationships and interests of transit agency and passengers.

Chapter 4. CTA Route 77 Application

This chapter investigates the relationships and applies the process described in Chapter 3 to the CTA bus route 77, Belmont. The objectives of this chapter are to understand how the theoretical relationships are working on a real route using real data and show how these relationships can be applied in the scheduling process. The route characteristics and the current schedule are described first including the trip time and passenger demand patterns obtained from the AVL and AFC systems. Then, the relationships described in Chapter 3 are estimated for route 77 during the AM peak. The unconstrained trip time distributions for both directions and a dwell time model for route 77 are estimated. The operational cost and service quality for route 77 which are estimated in the scheduling process are discussed. Then, the scheduling process proposed in Chapter 3 is applied to route 77. When the headway and schedule time are changed in this process, the trip time distribution, service quality and operational cost are all re-estimated based on these relationships. Finally, the trade-off between service quality and operational cost is presented.

4.1. Route 77 Characteristics

4.1.1. Route Description

The route chosen for the case study was route 77, Belmont of the Chicago Transit Authority, which covers Belmont Street, and part of Sheridan Street and Lake Shore Drive in the north portion of Chicago (see figure 4-1). Most eastbound trips start at the intersection of Belmont and Cumberland and most westbound trips start either at the Natural History Museum or at the intersection of Lake Shore Drive and Diversey. The starting (ending) point for the first (last) trips of vehicles being pulled-out (pulled-in) is at Belmont and Central. On the route, there are 11 time points indicating when the bus should be there but these time points are not used for holding to schedule in current operations.

The CTA provides service throughout the day between Central and Halsted on Belmont, between Central and Cumberland except between 1:45 and 3:30 AM, and between Halsted and Diversey on Lake Shore Drive, except between 12:40 and 5:00 AM. Between 7:00 AM and 7:15

PM the route is extended to the Natural History Museum. Most trips (more than 90%) start and end at Cumberland/Belmont, Diversey/Lake Shore Drive, or the Natural History Museum.

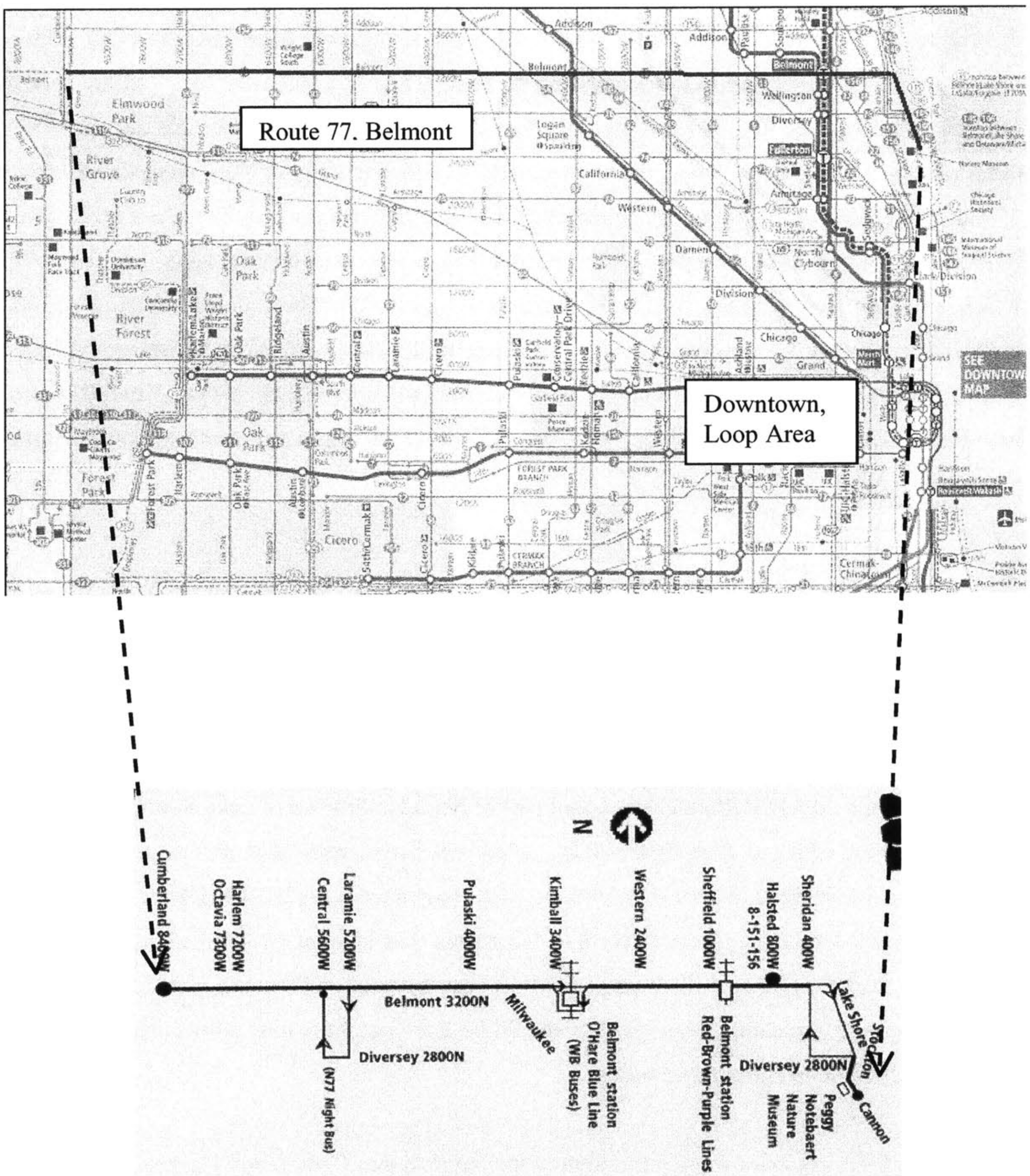


Figure 4-1 CTA Route 77, Belmont

4.1.2. Current Timetable

Schedule Time

The schedule time is the time allowed to move from one time point to the next. On route 77, there are 11 time points, which are used for scheduling purpose to indicate when the vehicle will depart. I chose 6 of the 11 time points, to summarize the scheduled times on route 77: Cumberland/Belmont, Octavis/Belmont, Central/Belmont, Halsted/Belmont, Diversey/Lake Shore, and the Natural History Museum. As indicated most trips on route 77 start or end at Cumberland, the Natural History Museum, or Lake Shore Drive. Central is a location where vehicles pull in and out of service. Halsted is another important point since there are connections there with Brown, Red, and Purple lines. The day is divided into 7 time periods; Early AM (before 6:30), AM peak (6:30 to 8:30AM), Morning (8:30AM to 12:30PM), Afternoon (Eastbound: 12:30 to 3:00PM, Westbound: 12:30 to 3:30PM), PM peak (Eastbound: 3:00 to 5:00PM, Westbound: 3:30 to 5:30PM), Evening (Eastbound: 5:00 to 8:00PM, Westbound: 5:30 to 8:00PM), and Night (after 8:00PM). The schedule times between time point pairs for each of the seven defined time periods and standard deviation of schedule time between time periods are summarized in the Table 4-1.

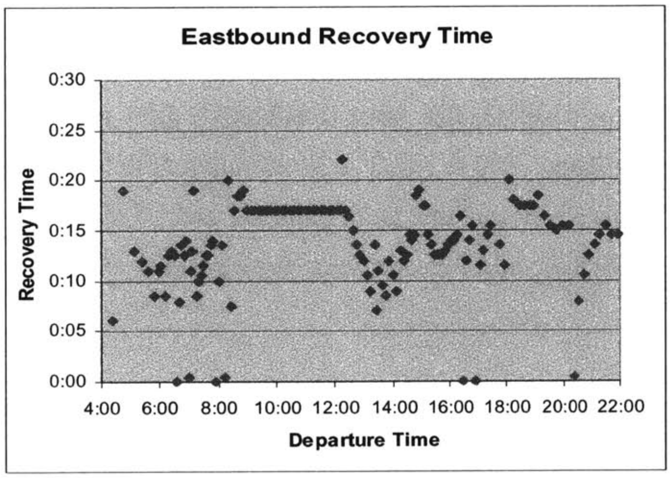
Eastbound	Cumberland - Octavis	Octavis - Central	Central - Halsted	Halsted - Lake Shore	Lake Shore - Natural Museum
AM Peak	5min 52sec	10min 20sec	46min 16sec	10min 6sec	-
Morning period	5min	9min 30sec	40min 9sec	10min 4sec	3min
Afternoon period	5min 27sec	10min 55sec	40min 46sec	10min	3min
PM Peak	5min 2sec	10min 2sec	49min 16sec	10min 59sec	3min
Evening period	4min 59sec	9min 3sec	44min 22sec	11min 5sec	3min
Std.	23 sec	43 sec	3min 48sec	32 sec	0
Westbound	Natural Museum - Deversey	Halsted - Lake Shore	Central - Halsted	Octavis - Central	Cumberland - Octavis
AM Peak	-	11min 53sec	40min 16sec	9min 18sec	4min 20sec
Morning period	3min	11min	37min	10min 21sec	4min 29sec
Afternoon period	3min	11min 36sec	40min 40sec	10min 57sec	5min 10sec
PM Peak	3min	12min 59sec	46min	12min 24sec	5min 32sec
Evening period	2min 34sec	8min 52sec	39min 57sec	11min 25sec	5min 16sec
Std.	13sec	1 min.31sec	3min 15sec	1min 10sec	31sec

Table 4-1 Schedule Time for Route 77

There are some significant variations in schedule time between periods particularly between Central and Halsted in the peak periods, however, in the each time period, the schedule times are homogeneous.

Recovery Time

Figure 4-2 shows the scheduled recovery time for route 77. It shows that there is considerable variation in recovery time on this route suggesting that recovery time is not set strictly on the trip time distribution and a desired on-time departure probability. In general recovery times range between 7 and 20 minutes representing 10 to 30 % of trip time.



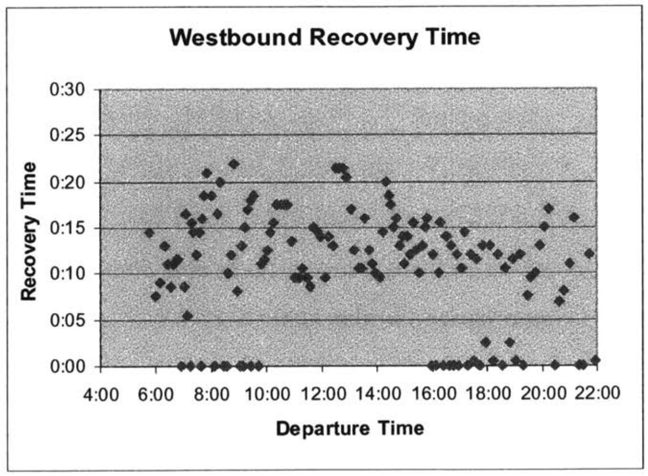


Figure 4-2 Recovery Time for Route 77

Headway

Vehicles run every 5 to 10 minutes except for night owl service (it operates at 30 minute intervals after midnight until the early AM period) and night period. The scheduled headways of eastbound trips between Central and Halsted are plotted in Figure 4-3 and show considerable variances in most time periods. This is due to some trips that start in the middle of the route such as at Octavis, Pacific, and Major and other trips which start or end at Central when vehicles are pulled in or pulled out of service.

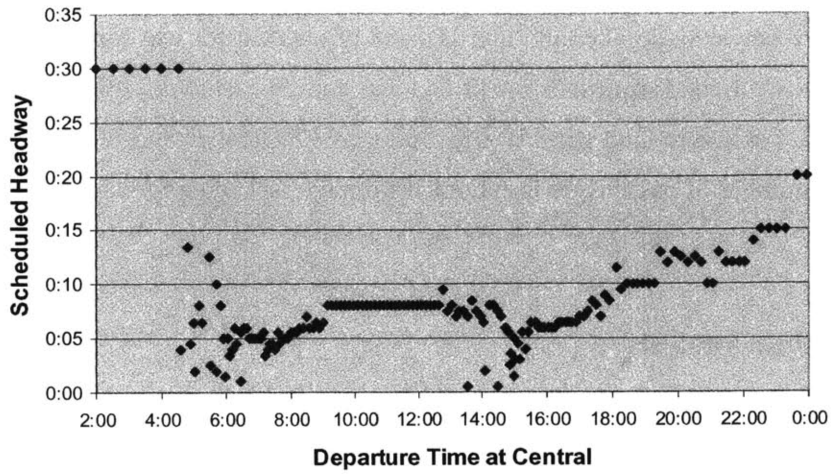


Figure 4-3 Eastbound Scheduled Headway (between Central and Halsted)

4.2. AVL and AFC Systems Data Analysis

4.2.1. Data

For this case study, vehicle location data were obtained from the Automatic Vehicle Location (AVL) system and passenger boarding data were obtained from Automatic Fare Collection (AFC) System on 17 and 18 October, 2001. This AVL system data for each bus every 6 seconds provides the longitude and latitude of vehicle location, vehicle speed, and whether the door is open or not. From the AVL data, it is possible to divide trip time into dwell time and movement time by using vehicle speed and door open information. Also, from the location information, we can find the segment times between time points. The AFC system provides the time of passenger boarding and run number of each bus. From the AFC data, the number of passenger boarding on a trip can be obtained. By comparing the run number in the AVL and AFC data, the impact of number of passenger boarding on the trip time can be estimated. However, since the location information is not provided in the AFC data, neither the number of passenger boarding per stop nor the maximum load can be obtained. Due to missing data from AVL system, it is rare to have data for two successive runs. Therefore, it was not possible to have enough headway information from AVL data to perform the headway analysis proposed in Chapter 3.

Since route 77 has multiple terminals the entire route was not considered. Instead the core of the route between Cumberland and Halsted is selected for trip time analysis. From the AVL system, 54 eastbound trip times on 17 October and 71 eastbound trip times on 19 October were extracted. For westbound trip, 59 trip times on 17 October and 69 on 18 October were extracted. The number of passengers is extracted from the AFC data for each trip recorded by the AVL system.

4.2.2. Trip Time Analysis

Overview

Table 4-2 shows a statistical summary of both scheduled and actual trip times. For both directions, the PM peak has the longest trip times and the Morning period has the shortest trip times. Trip time variability is slightly greater westbound than eastbound.

Eastbound	**Count**	**Average (min)**	**Standard Deviation (min)**	**Schedule Time (min)**
AM Peak	17	61.0	4.0	62.0
Morning period	31	55.0	4.1	54.5
Afternoon period	28	61.0	4.5	57.5
PM Peak	17	66.0	2.2	65.0
Evening period	21	61.0	5.8	57.5
All Periods		60.0	5.5	
Westbound				
AM Peak	19	56.0	4.2	54.0
Morning period	35	54.5	3.2	52.0
Afternoon period	30	61.0	6.4	56.5
PM Peak	18	70.0	5.0	64.0
Evening period	18	59.0	9.4	55.0
All Periods		59.3	7.5	

Table 4-2 Trip Time statistics by Time Period

Figure 4-4 and 4-5 show the actual trip time compared with the current scheduled times both eastbound and westbound. The scheduled trip time follows the general trend of actual trip time (i.e. high trip times during peak hours and sharp decline of trip time after the PM peak). From these figures, we can see that actual trip times, in general, are greater than scheduled times and this is more pronounced for the westbound direction particularly in the PM period.

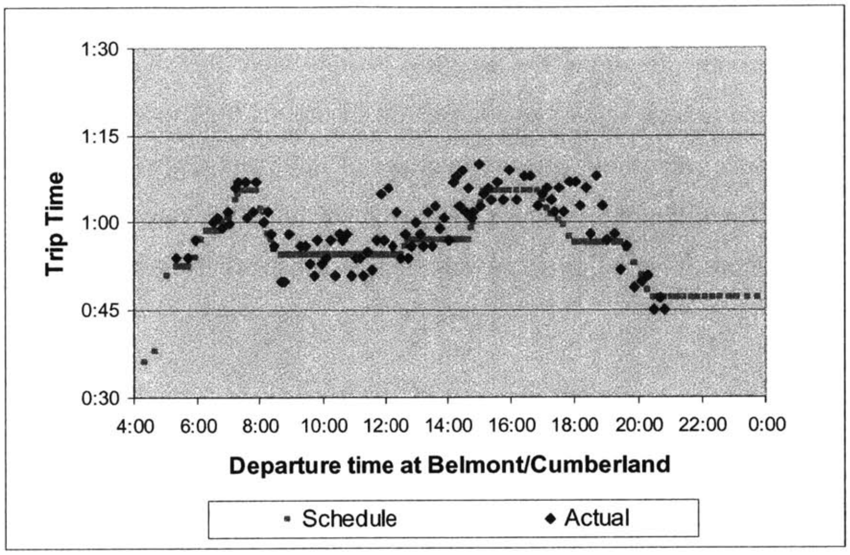


Figure 4-4 Eastbound Scheduled and Actual Trip Time

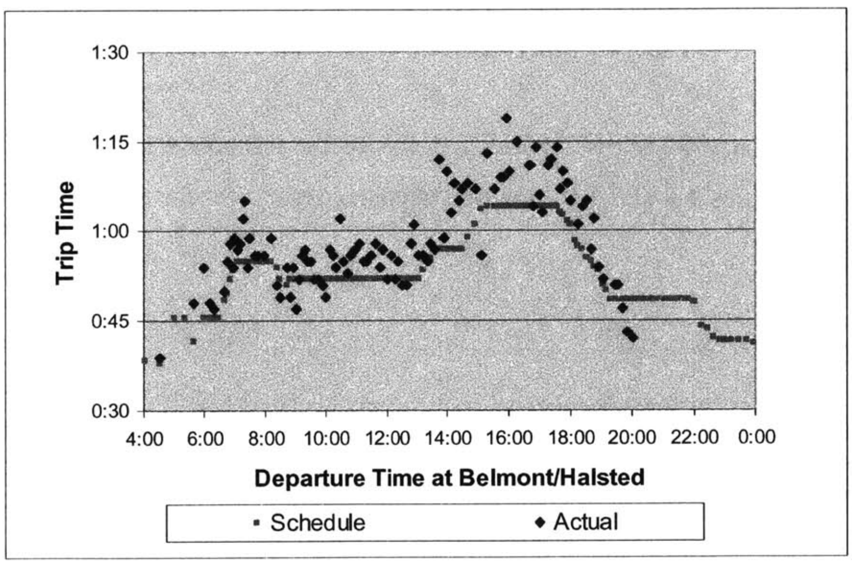


Figure 4-5 Westbound Scheduled and Actual Trip Time

Dwell Time and Movement Time

As discussed in Chapter 3, the vehicle trip time can be divided into vehicle movement time and dwell time using the AVL data. The total dwell time for a trip was estimated by summing the times when the door is open and vehicle speed is less than 0.1 mile/hour and the movement time was estimated by subtracting the dwell time from the vehicle trip time. Table 4-3 shows a statistical summary of both movement and dwell times. For both directions, the PM peak has the longest times for both movement and dwell. While the morning period has the shortest movement times in both directions the evening periods have the shortest dwell times. The variance of dwell time is high when the average dwell time is high in general. This shows that the dwell time variance increases with the increase of the average dwell time as mentioned in Section 3.2.3. In all periods, the variance of movement time is greater than that of dwell time although the coefficient of variation for dwell time is substantially greater than for movement time.

	EastBound				WestBound			
	Movement Time		Dwell Time		Movement Time		Dwell Time	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
AM peak	51.57	4.35	9.63	2.99	48.11	3.42	8.03	2.74
Morning	46.51	2.62	9.58	3.25	46.37	3.13	8.43	2.46
Afternoon	50.41	3.98	10.32	3.75	51.03	5.15	10.89	3.35
PM peak	54.45	3.02	11.24	2.28	55.40	5.09	13.18	3.06
Evening	52.03	4.22	8.24	3.99	51.02	6.43	7.98	3.73
All Periods	48.32	4.48	9.78	3.41	49.80	5.47	9.57	3.52

Table 4-3 Movement and Dwell Times Statistics

Figures 4-6 and 4-7 show the dwell times for the eastbound and westbound directions respectively and Figures 4-8 and 4-9 show the movement times for the eastbound and westbound directions respectively.

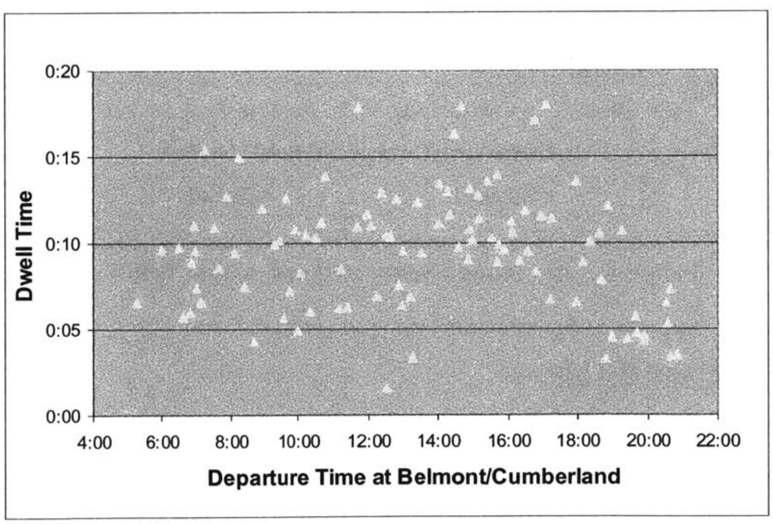


Figure 4-6 Eastbound Dwell Time

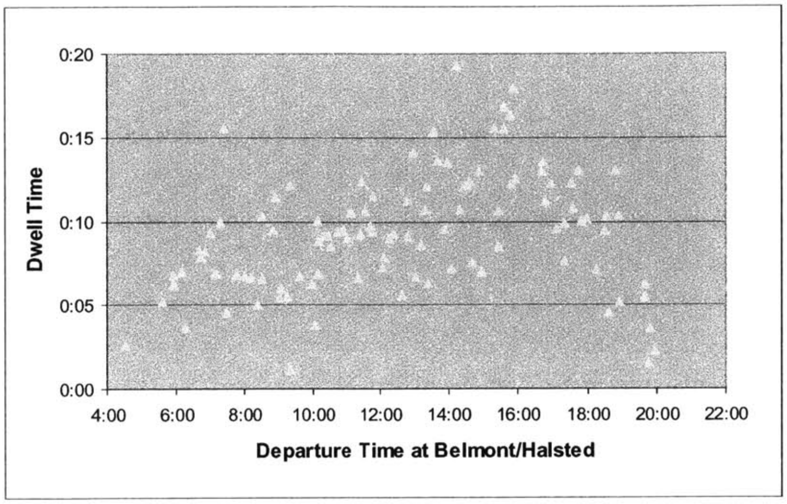


Figure 4-7 Westbound Dwell Time

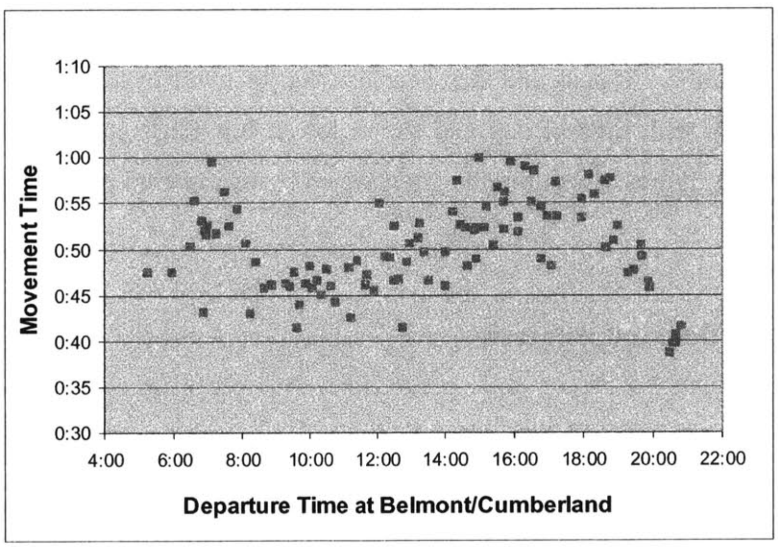


Figure 4-8 Eastbound Movement Time

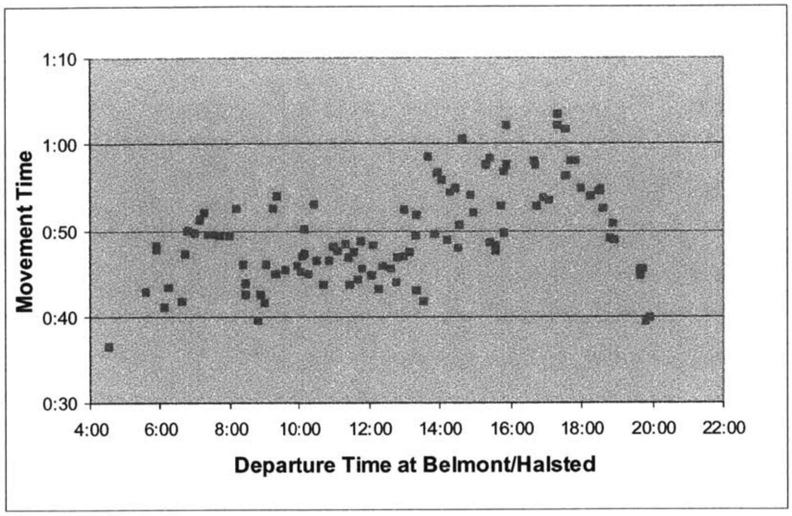


Figure 4-9 Westbound Movement Time

There is no distinguishable pattern in the eastbound dwell times beyond the late evening having lower dwell time and the PM peak having higher values. The westbound dwell times generally increase till the PM peak and then decrease sharply in the evening. The movement time changes more clearly with time of day and shows lower, but still significant variability in any period. As shown in figures, dwell time is not affected by time period as much as the movement time is.

4.2.3. Passenger Demand Analysis

The number of passengers boarding a bus was extracted from the AFC data to estimate the average passenger arrival rate. An AFC transaction indicates a passenger boarding at a certain time. Therefore, the total passengers boarding on the trip can be obtained by summing AFC transactions during the trip. Eastbound passenger boarding data was extracted for 114 trips and westbound passenger boarding data for 118 trips. From 4:00 AM to 10:00PM, the total passengers boarding data were divided into 2 hour periods and the average boardings per trip for each time period was estimated. Since we do not have the number of passengers boarding for all bus trips, the total passenger demand during the time period was estimated by multiplying the number of scheduled trips by the average number of passengers boarding per trip. Then the passenger arrival rate (number of passenger per 10 minutes) by time period was estimated to show the passenger demand variation on route 77. Figure 4-10 illustrates the resulting time of day variation of passenger demand.

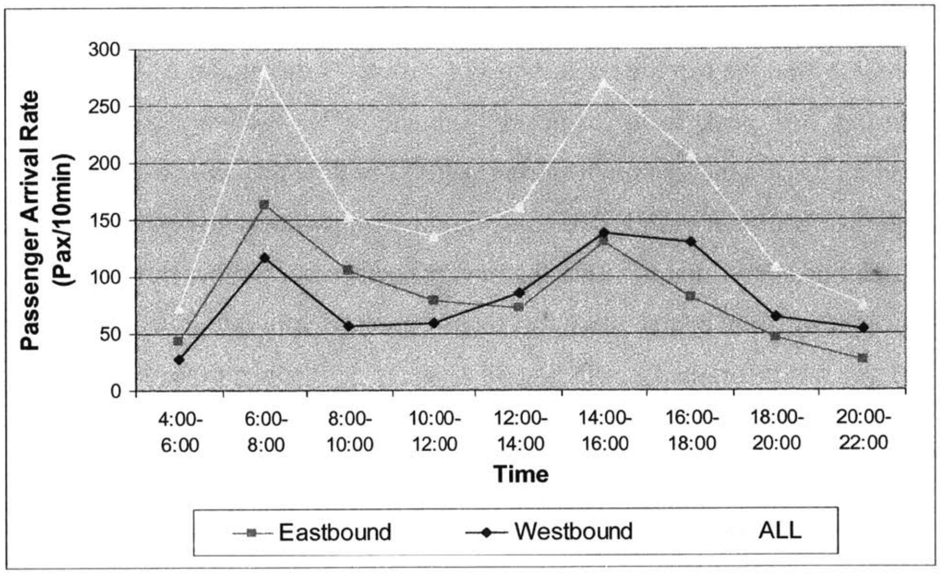


Figure 4-10 Passenger Arrival Rate

For the eastbound direction, passenger demand is highest in the AM peak, from 6:00 to 8:00 AM, consistent with commuting trips into the city. For westbound trips, passenger demand is highest between 2:00 and 6:00 PM due to the flow back toward residential areas. Overall, there are peaks in passenger demand which are between 6:00 and 8:00AM and between 2:00 and 6:00PM due to work and school trips.

4.3. Trip Time Distribution and Dwell Time Model Estimation

In this section, I will estimate the trip time distribution and dwell time model needed for the scheduling process for route 77 during the AM peak. First of all, the current unconstrained trip time distribution is estimated from the observed data with the distribution fitting software, ARENA. Due to the route characteristic that different trips cover different route segments, I deal only with the route segment between Cumberland and Halsted on Belmont, which is the trunk portion covered by most trips. The number of passengers boarding and alighting at each stop is not available from the AFC data, and thus a dwell time model at the stop level cannot be estimated. Instead using the total passengers boarding information, aggregate dwell time models at the trip level are estimated.

4.3.1. Trip Time Distribution Estimation

In order to find the trip time distribution for route 77 during the AM peak, additional trip time data during AM peak were extracted from the AVL system producing a total of 86 eastbound and 83 westbound trip times during the AM peak which were used for generating trip time distributions. Unlike the AVL data used for the earlier data analysis, this data indicates the location of each bus every minute rather than every 6 seconds. Neither does it provide the door open and close information and so these trip times cannot be split into dwell time and movement time. Based on the theoretical discussion in Chapter 3, the trip time distribution should be modified to eliminate the trip time variability caused by the headway variability to obtain the unconstrained trip time distribution. However without splitting the trip time into dwell time and movement time components, this was not possible. Thus, the trip time distribution obtained from the observed data is assumed to be acceptable and free of any significant headway variability effect.

Table 4-4 is a summary of the trip time statistics for sub-periods during the AM peak in both directions. As shown in Table 4-4, the eastbound average trip times in the heart of the period, between 7:00 and 8:00 PM, are higher than those of the remainder of the peak, between 6:30-7:00 AM and 8:00-8:30 AM. The westbound average trip times appear more stable across the AM peak. Therefore, the t-test is applied to see if there are any systematic trip time differences between two sub-periods, the main peak (from 7:00 to 8:00 AM) and other periods (from 6:30 to 7:00 and from 8:00 to 8:30) within the AM peak. The t-statistic value of 0.231 westbound and 5.144 eastbound confirm that there are systematic trip time differences within the AM peak eastbound but not westbound at the 95% level of significance.

EastBound

Sub-period	Count	Average Trip Time	Standard Deviation
6:30-7:00	24	59.75	4.95
7:00-7:30	23	63.52	5.37
7:30-8:00	17	65.12	2.87
8:00-8:30	22	58.55	3.78
AM peak	86	61.51	5.10

WestBound

Sub-period	Count	Average Trip Time	Standard Deviation
6:30-7:00	18	56.50	3.54
7:00-7:30	28	57.29	3.60
7:30-8:00	18	55.72	3.20
8:00-8:30	19	56.47	4.02
AM peak	83	56.59	3.59

Table 4-4 Statistics of Trip Times of Sub-time Periods during AM peak

Based on the trip time data, I found the distribution best representing the unconstrained trip times with the distribution fitting software, ARENA. The gamma distribution, lognormal and normal distribution are considered as possible distributions to represent the actual trip times. Table 4-5 summaries the AVL data statistics as well as the best fit parameters for the gamma, lognormal and normal distributions. The chi-square goodness-of-fit test is performed and the calculated χ^2 value for each direction and the corresponding critical value $\chi^2_{0.05}$ are compared in the table. According to the chi-square goodness-of-fit test, the normal and gamma distributions for both directions pass the test while the lognormal distributions do not.

Figures 4-11 and 4-12 show the actual trip time data along with the normal and gamma distribution of trip time for both directions while Figures 4-13 and 4-14 show the cumulative distributions. As shown in these figures, the normal distribution has a substantially better fit to the actual data than the gamma distribution as is also indicated by the square error and χ^2 test values. Therefore, the trip time of CTA route 77 during the AM peak follows a normal distribution.

		Eastbound	Westbound
Count		40	83
Statistics	Mean	64.2	56.67
	Std	4.5	3.49
	Min	57	50
	Max	76	65
Gamma Distribution	α	2.61	2.22
	β	3.98	3.23
	T_{min}	56.5	49.5
	Square Error	0.0217	0.022
	χ^2	3.66	7.14
Lognormal Distribution	Mean	8.58	7.54
	Std	6.65	5.49
	T_{min}	56.5	49.5
	Square Error	0.0303	0.027
	χ^2	10.3	11.8
Normal Distribution	Mean	64.5	56.7
	Std	3.96	3.46
	Square Error	0.015	0.018
	χ^2	3.58	6.66
χ^2 test	$\chi^2_{0.05}$	7.81	7.81

Table 4-5 Statistics of Trip Times

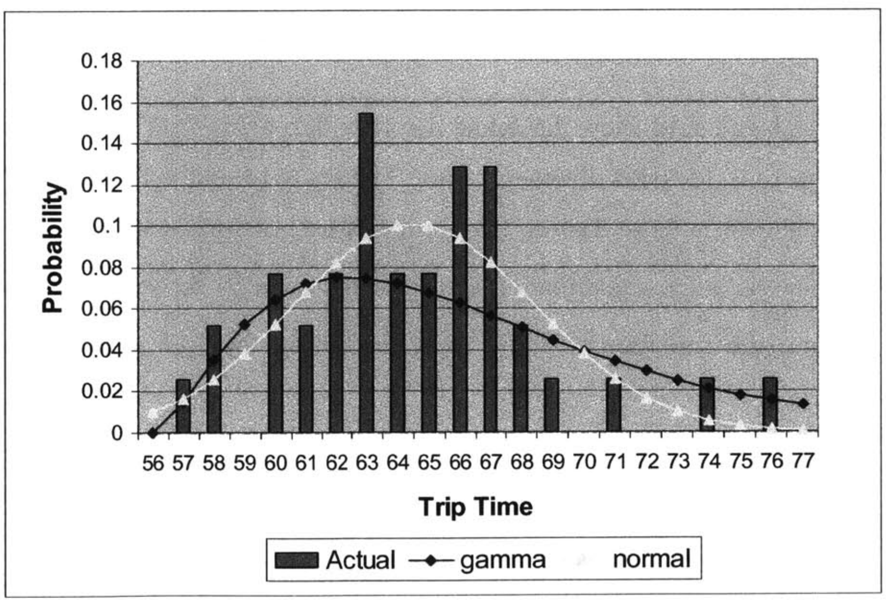


Figure 4-11 Eastbound Probability Distribution

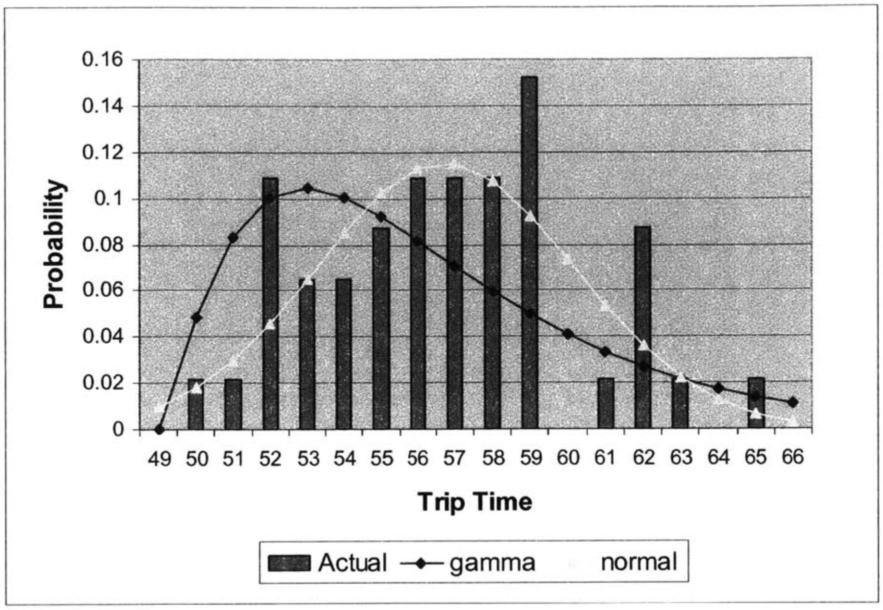


Figure 4-12 Westbound Probability Distribution

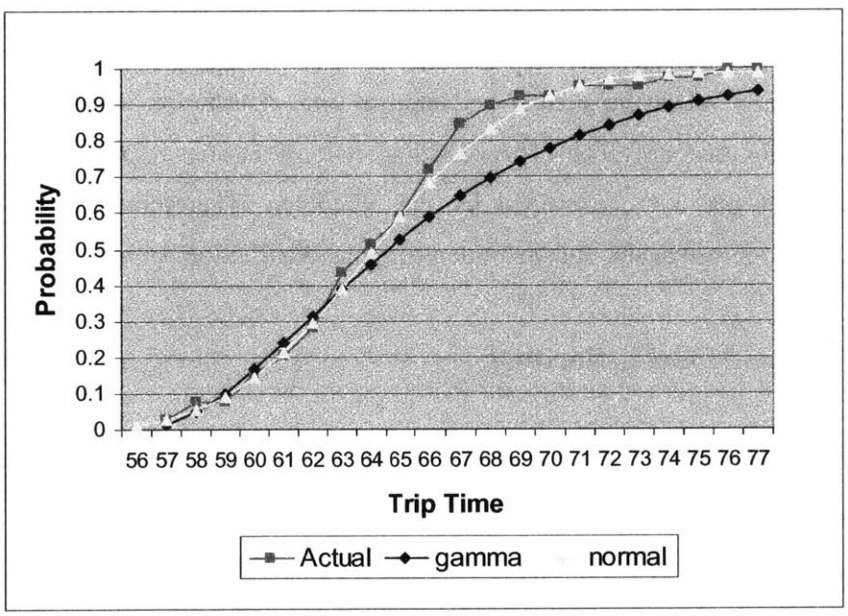


Figure 4-13 Eastbound Cumulative Probability Distribution

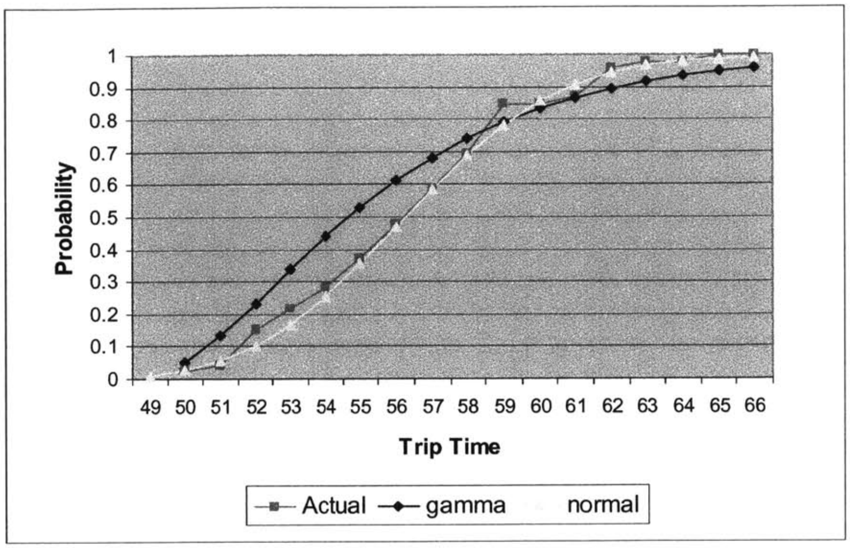


Figure 4-14 Westbound Cumulative Probability Distribution

The eastbound scheduled trip time is 65 minutes and the westbound is 55 minutes from 7:00 to 8:00 AM. 60% of eastbound trips and 37% of westbound trips are expected to be early under the current schedule. Also, as stated above, the trip time distributions for both directions follow normal distributions. If schedule-based holding is implemented, the percentage of vehicles that are early would be smaller and the trip time distribution would be skewed to the right. This confirms that on route 77, no holding strategy is now implemented and thus, the observed trip times are not constrained by the schedule. Therefore, the current trip time distribution will be viewed as the unconstrained trip time distribution for route 77.

4.3.2. Dwell Time Model Estimation

As derived in Section 3.3.3, the total dwell time at the trip level is expected to be a function of total passenger demand. The dwell time data obtained from the AVL system and number of passengers obtained from AFC data is used to estimate a dwell time model for route 77. First, outlier analysis was performed in order to eliminate data errors and improve the fit of model. As a result, 3 data points that have large deviations from the predicted values were eliminated and the corrected R^2 value of the simple linear model without the outliers was improved by about 0.06 comparing to that with the complete data set. The dwell time models were estimated eastbound and westbound separately recognizing that different patterns of boarding and alighting could require different handling time and thus dwell time modes might be different by direction.

Figures 4-15 and 4-16 show the relationship between total dwell time per trip and aggregate passengers served per trip in the eastbound and westbound directions respectively and they both show a strong relationship. A regression analysis was performed using the SST (Statistical Software Tools) software.

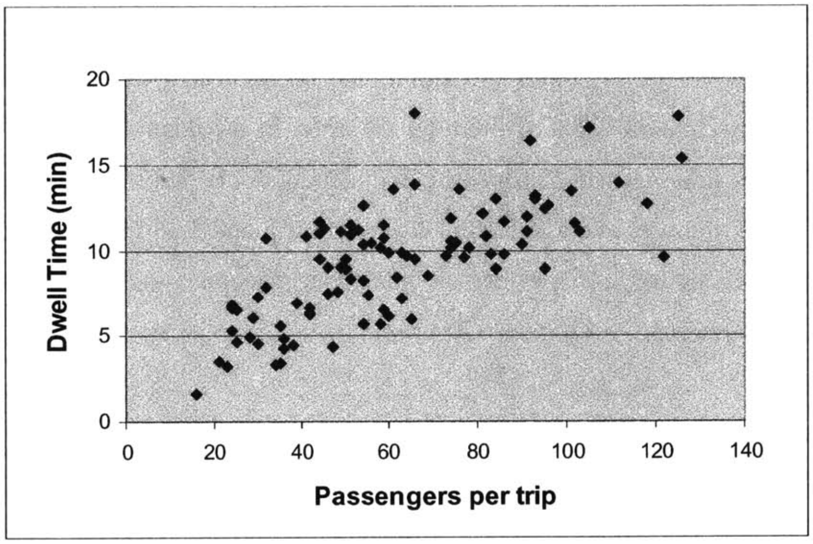


Figure 4-15 Relationship between Total Dwell Time and Passenger Demand (Eastbound)

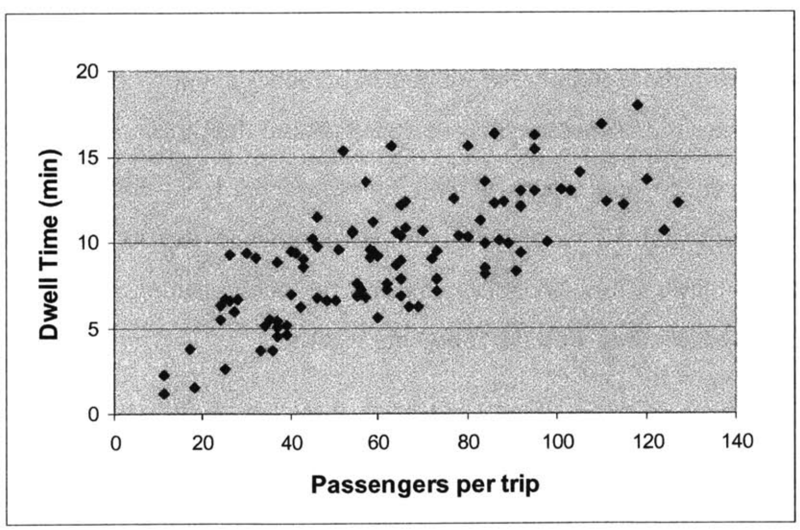


Figure 4-16 Relationship between Total Dwell Time and Passenger Demand (Westbound)

A simple linear model assuming that only the total number of passengers affects the dwell time is tested first. The resulting model is shown below:

Eastbound: $DT_i = 3.67 + 0.093 * L_i$ (4-1)

(6.140) (10.329) ($R^2 = 0.521$)

Westbound: $DT_i = 3.36 + 0.093 * L_i$ (4-2)

(5.637) (10.649) ($R^2 = 0.522$)

Both the coefficients of these models are significant (as indicated by the t-statistics) and the models explain approximately 52% of the total variation in the data set. These simple models suggest that the total time per trip for opening and closing doors and other overhead for making stops was about 3.67 minutes average for the eastbound trip and 3.36 minutes for the westbound trip. The average processing time per person was about 6 seconds including both boarding and alighting for both directions.

The next type of model estimated recognizes the fact that the sum of door opening and closing time may be related to the total passengers boarding. If there is low passenger demand on a bus trip, the bus may skip some stops where there is no passenger boarding or alighting, and in this case the sum of door opening and closing time may not be constant. However, if there is high demand on a bus trip, the bus might need to stop at all the bus stops, and thus the sum of door opening and closing time will be constant. From Figure 4-15 and 4-16, it can be seen that dwell time is increasing more steeply before demand reaches about 50 passengers than after that. Different thresholds around 50 passengers are tested to find the threshold that best represents the dwell times pattern, and 55 passengers, at which the corrected R^2 value are highest, are selected for the eastbound trip and 50 passengers for the westbound trip as the threshold value for passengers per trip. Dwell time models including the door opening and closing terms in the simple linear model were tested with the following results:

$$\text{Eastbound: } DT_i = 6.00 * \begin{cases} 1, \text{ if } L_i \geq 55 \\ 0. \text{ otherwise} \end{cases} + 0.11 * \begin{cases} L_i, \text{ if } L_i < 55 \\ 0. \text{ otherwise} \end{cases} + 0.064 * L_i \qquad (4\text{-}3)$$

(2.74) (5.23) (5.38) ($R^2 = 0.535$)

$$\text{Westbound:}\quad DT_i = 5.42 * \begin{cases} 1, \; if\, L_i \geq 50 \\ 0. \; otherwise \end{cases} + 0.11 * \begin{cases} L_i, \; if\, L_i < 50 \\ 0. \; otherwise \end{cases} + 0.068 * L_i \qquad (4\text{-}4)$$

$$(2.512) \qquad\qquad (6.139) \qquad\qquad (4.716) \quad (R^2 = 0.531)$$

The coefficients of these models are also significant (as indicated by the t-statistics) and the corrected R^2 values are improved by about 0.01 comparing to the simple linear models. The constant value increases since it represents the average door opening and closing time of vehicles stopping at all stops. The passenger handling time including the total passenger demand impacts on the number of stops that a vehicle actually makes is around 11 seconds for both directions when there is small demand on the vehicle.

The other type of model tested were combining two linear models one of which applies when the demand is less than a threshold value and the other when the demand is above this level. As with the previous model, when the passenger demand threshold is 55 for the eastbound and 50 for the westbound, the model has the highest corrected R^2 value and is shown below:

$$\text{Eastbound:}\quad DT_i = 0.98 * \begin{cases} 1, \; if\, L_i < 55 \\ 0. \; otherwise \end{cases} + 0.15 * \begin{cases} L_i, \; if\, L_i < 55 \\ 0. \; otherwise \end{cases}$$

$$(0.931) \qquad\qquad (4.918)$$

$$+ 5.71 * \begin{cases} 1, \; if\, L_i \geq 55 \\ 0. \; otherwise \end{cases} + 0.068 * \begin{cases} 1, \; if\, L_i \geq 55 \\ 0. \; otherwise \end{cases} \qquad (4\text{-}5)$$

$$(2.529) \qquad\qquad (5.126) \qquad\qquad (R^2 = 0.541)$$

$$\text{Westbound:}\quad DT_i = 1.25 * \begin{cases} 1, \; if\, L_i < 50 \\ 0. \; otherwise \end{cases} + 0.15 * \begin{cases} L_i, \; if\, L_i < 50 \\ 0. \; otherwise \end{cases}$$

$$(0.910) \qquad\qquad (5.028)$$

$$+ 4.97 * \begin{cases} 1, \text{ if } L_i \geq 50 \\ 0. \text{ otherwise} \end{cases} + 0.074 * \begin{cases} 1, \text{ if } L_i \geq 50 \\ 0. \text{ otherwise} \end{cases} \quad (4\text{-}6)$$

(3.192) (4.974) ($R^2 = 0.535$)

All coefficients except the intercept when demand is less than 55 or 50 are significant (as indicated by t-statistics) and the corrected R^2 value is improved by 0.015 comparing to the simple linear model. The larger coefficient of the second term than the last term means that the dwell time is increasing more steeply before demand reaches about 55 passengers per trip than after that.

The last type of model suggested in Chapter 3 includes the passenger friction term when there is high passenger demand on the bus. However, in Figures 4-15 and 4-16, there is no evidence of extra dwell time as a function of passenger congestion when the passenger demand is high. Different types of friction term were included in the dwell time model, but none improved over the simple linear model and just makes the model more complex.

Different types of dwell time models were tested to find a dwell time function for route 77. Both models considering the door opening and closing time (equations 4-3 and 4-4) and combining two linear models (equations 4-5 and 4-6) improve the corrected R^2 value over the simple linear models (equations 4-1 and 4-2). The combined models (equations 4-5 and 4-6) have better fit as indicated in the corrected R^2 values than other models (equations 4-3 and 4-4). Since the models are simple to apply and explain the dwell time better than the simple linear models, equations 4-5 and 4-6 are considered as eastbound and westbound dwell time models for route 77.

4.4. Relationships Estimation

In this section, I will estimate the relationships developed in Chapter 3. First, based on the unconstrained trip time distribution and dwell time model of route 77 estimated in Section 4.3, the relationships between the trip time distribution and the schedule parameters are estimated. Then, the inter-relationships between schedule parameters are estimated.

4.4.1. Trip Time Distribution and Schedule Time

As discussed in Chapter 3, the schedule parameters determine the shape of the trip time distribution and then the trip time distribution is used to determine the schedule parameters. The trip time distributions are mainly affected by the schedule time and headway. The spreadsheet-based model to estimate the trip time distribution is used to generate the trip time distribution when the schedule time changes. The dwell time model is used to generate the unconstrained trip time distribution when the headway changes.

In order to apply the model to estimate the trip time distributions with different schedule times, some assumptions are made about the trip time distribution for route 77. First of all, 4 possible holding points are assumed on the route excluding the starting point and ending point and so the route is divided into 5 route segments. Since only trip times from the starting point to the ending point are readily available, assumptions about distributions of segment times are also needed. In the interest of simplicity all segments are assumed to have the same distance and the same segment time distribution. Also, the sum of segment time distributions will comprise the current trip time distribution. As shown in Section 3.2.1, the critical decisions that determine the trip time distribution are the location and schedule time of the last time point. Thus, assumptions about the location and schedule time of the last time point are necessary. The last holding point is assumed to be the fourth possible holding point which is located at the 4/5 point of the route. The initial schedule time at the last time point is set to the time which makes 20% of trips early at the last time point since below this minimum schedule time, the trip time distributions does not change significantly and thus the operational costs are the same as the initial schedule time with worse service quality then the initial schedule time. The schedule time will be is increased by 2 minutes at the last time point to investigate the effect of the schedule time on the trip time distribution. The last scheduled segment time is always set to the average segment time.

The unconstrained trip time distribution is the current trip time distribution estimated in section 4.3.1, which has a mean of 64.5 minutes and a standard deviation of 3.96 minutes eastbound, and a mean of 56.7 minutes and a standard deviation of 3.46 minutes westbound. With the assumption that the 5 segments along the route have the same distance and segment time distributions, the segment time distribution of eastbound trips is assumed to follow a normal distribution with a mean of 12.9 minutes and a standard deviation of 1.77 minutes. The westbound segment times are also assumed to follow a normal distribution with a mean of 11.3 minutes and a standard deviation of 1.55 minutes.

The eastbound and westbound trip time distributions with different schedule trip times are shown in Figures 4-17 and 4-18. These figures show that longer schedule time shifts the trip time distribution to the right producing a longer expected trip time and smaller variance as described in Chapter 3.

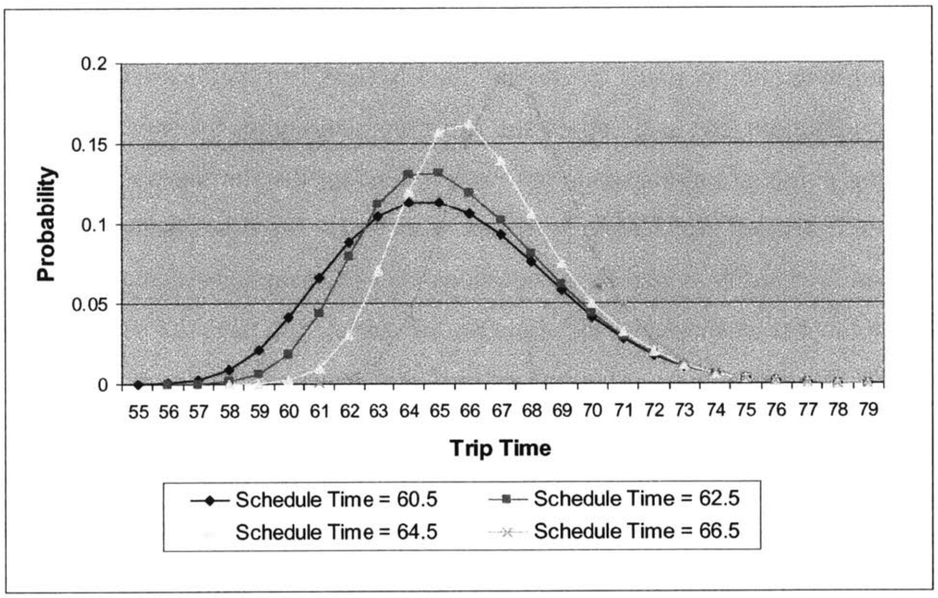


Figure 4-17 Eastbound Trip Time Distributions with Different Schedule Times

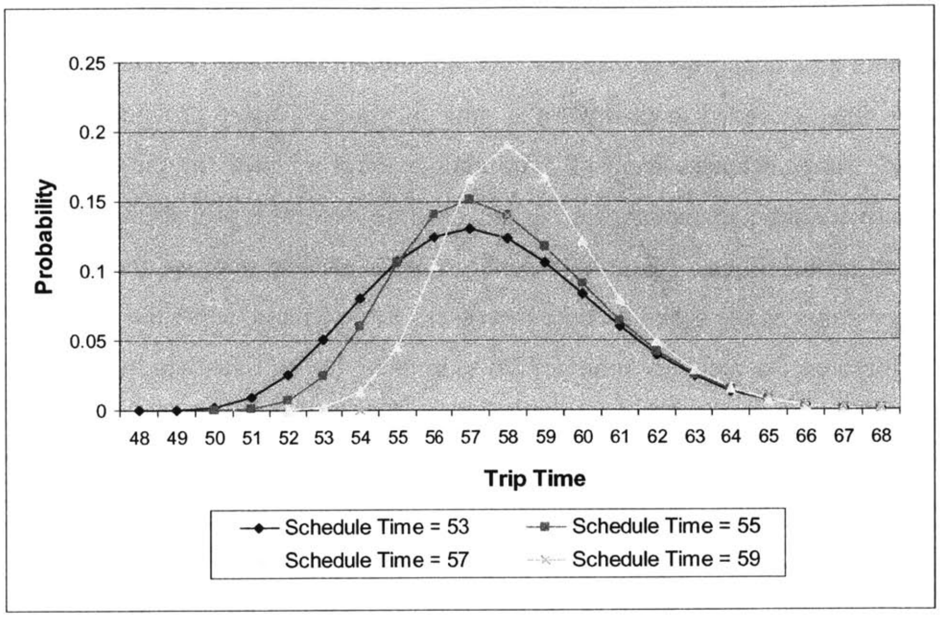


Figure 4-18 Westbound Trip Time Distributions with Different Schedule Times

The half cycle time and recovery time will be set based on the desired on-time departure probability at the starting terminal after estimating the trip time distribution based on the schedule time. Tables 4-6 and 4-7 summarize the schedule times, half cycle times and recovery times for the current headway in both directions. The schedule time is determined based on the on time arrival probability and half cycle time and recovery time are determined based on the on time departure probability.

Schedule Trip Time		60.5		62.5		64.5		66.5	
		Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time
On Time Departure Probability	85%	7.5	68	6	68.5	4.5	69	3	69.5
	90%	8.5	69	7	69.5	5.5	70	3.5	70
	95%	10	70.5	8	70.5	6.5	71	4.5	71
	97%	11	71.5	9	71.5	7.5	72	5.5	72

Table 4-6 Eastbound Schedule Parameters in minutes

Schedule Trip Time		53		55		57		59	
		Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time
On Time Departure Probability	85%	7	60	5	60	3.5	60.5	2	61
	90%	8	61	6	61	4	61	3	62
	95%	9	62	7	62	5	62	4	63
	97%	10	63	8	63	6	63	4.5	63.5

Table 4-7 Westbound Schedule Parameters in minutes

From these tables, we can find the relationship between schedule time and recovery time given desired on time departure probability. As indicated in the tables, if schedule time increases, less recovery time is needed to maintain the same on time departure probability. For example, when schedule time increases from 60.5 minutes to 66.5 minutes for the eastbound trip, the necessary recovery time to maintain a certain on time departure probability decreases by 3-5 minutes for all probabilities. Also, the recovery time needed to improve the on-time departure probability decreases as the schedule time increases. For example, when the eastbound schedule time is 60.5 minutes, the recovery time needed to improve the on time departure probability from 90% to 95% increases by 1.5 minutes while it increases by 1 minute at other schedule times. In order to show the relationship between schedule time and recovery time, Figure 4-19 was generated from Table 4-7.

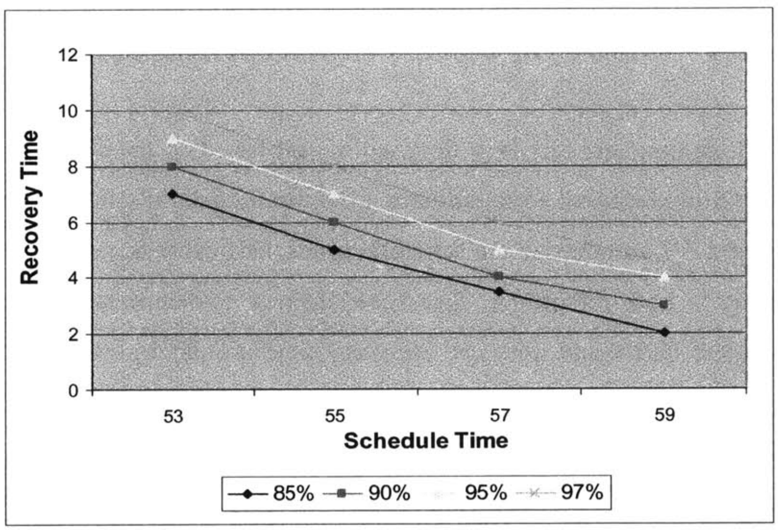


Figure 4-19 Relationship between Schedule Time and Recovery Time (Westbound)

Given a targeted on time departure probability (each line indicates a different on time departure probability), the necessary recovery time decreases as schedule time increases. It decreases sharply when the schedule time is short and then it decreases less rapidly as schedule time increases. Thus the improved on time arrival probability due to increased schedule time decreases the need for recovery time to maintain on time departures. If there is a minimum required recovery time, this will set a bound on possible reduction in recovery time as schedule time increases. However, as the schedule time increases, less recovery time is needed to improve the on time departure probability.

However, some recovery times in Tables 4-6 and 4-7 are not realistic since they are less than 10 percent of trip time. Usually, transit agencies use the minimum recovery time of 10 percent of trip time and the recovery times of route 77 range between 7 and 20 minutes. Therefore it is reasonable to have a minimum recovery time for route 77 in this simplified case study and it is assumed to be 5 minutes. With this minimum recovery time, the schedule parameters under current headway change. The changed schedule parameters are summarized in Table 4-8.

Eastbound

Schedule Trip Time		60.5		62.5		64.5		66.5	
		Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time
On Time Departure Probability	85%	7.5	68	6	68.5	5*	69.5	-	-
	90%	8.5	69	7	69.5	5.5	70	-	-
	95%	10	70.5	8	70.5	6.5	71	5*	71.5
	97%~	11	71.5	9	71.5	7.5	72	5.5	72

Westbound

Schedule Trip Time		53		55		57		59	
		Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time
On Time Departure Probability	85%	7	60	5	60	-	-	-	-
	90%	8	61	6	61	-	-	-	-
	95%	9	62	7	62	5	62	-	-
	97%~	10	63	8	63	6	63	5*	64

* Minimum recovery time used

Table 4-8 Changed Schedule Parameters with Minimum Recovery Time

When either the schedule time is long or the on time departure probability is not high, the recovery times are set to the minimum recovery. As the schedule time increases, the on time departure probability that can be achieved by the minimum recovery time also increases.

4.4.2. Trip Time Distribution and Headway

Any change of headway will affect the typical number of passengers served by a bus, which will in turn affect the dwell time. However, the vehicle movement time will remain the same regardless of headway (see Chapter 3). Expected trip time for any headway will be the sum of movement time and the estimated dwell time based on the expected number of passengers served. As discussed in Chapter 3, the unconstrained trip time distribution could be obtained by adding movement time distribution and dwell time distribution. If we assume that only the mean of the dwell time distribution will be changed when the headway changes due to the change of the number of passenger served by a bus, the trip time distribution will be shifted by the change of mean dwell time.

In order to estimate the dwell time, the passenger demand during the AM peak is divided into 2 sub-time periods. The passenger demands and dwell times estimated by the dwell time model are summarized in Table 4-9.

	Eastbound		Westbound	
Sub-period	Demand/bus	Dwell Time	Demand/bus	Dwell Time
7:00-7:30	80	11.12	66	9.83
7:30-8:00	71	10.50	57	9.17

Table 4-9 Passenger Demand and Dwell Time

We can estimate the passenger demand on a trip with the assumption that total passenger demand will remain the same even if the headway changes. Also, with the change of passenger demand, the dwell time can be estimated with the total dwell time model estimated for route 77. Current average scheduled headways are 5 minutes for eastbound trips and 6 minutes for westbound trip. Table 4-10 shows the expected passengers per trip and estimated dwell times when headways are increased or decreased by 1 minute from current levels.

Eastbound

	6 minutes headway		4 minutes headway	
Sub-period	Demand/bus	Dwell Time	Demand/bus	Dwell Time
7:00-7:30	96	12.20	64	10.04
7:30-8:00	85	11.46	57	9.54

Westbound

	7 minutes headway		5 minutes headway	
Sub-period	Demand/bus	Dwell Time	Demand/bus	Dwell Time
7:00-7:30	77	10.64	55	9.02
7:30-8:00	67	9.87	48	8.47

Table 4-10 Passenger Demand and Dwell Time with Changed Headway

As shown in Tables 4-9 and 4-10, the dwell times increase (decrease) when headway increases (decreases). In Figures 4-20 and 4-21, the trip time distributions with different headways are presented. As the headway increases, due to the increase of dwell time, the trip time distribution moves to the right.

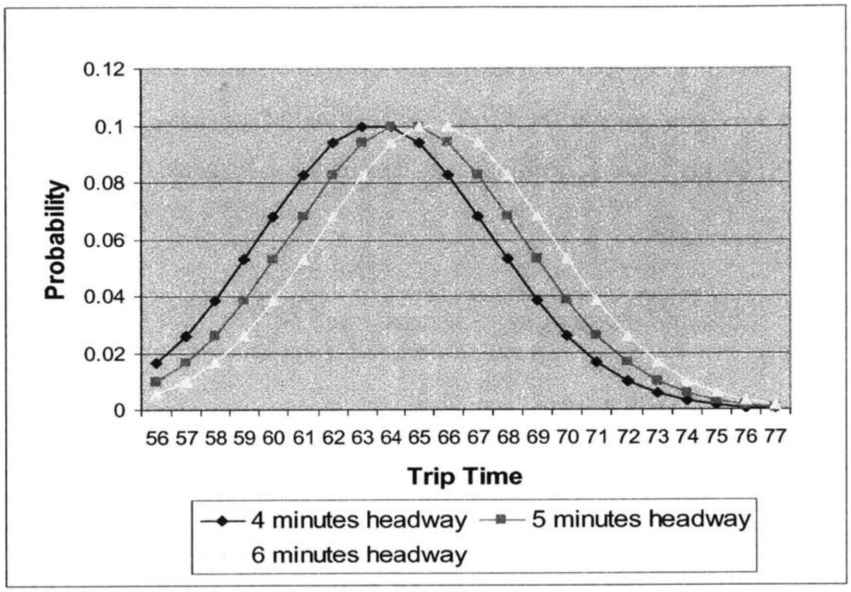


Figure 4-20 Eastbound Trip Time Distributions with Different Headways

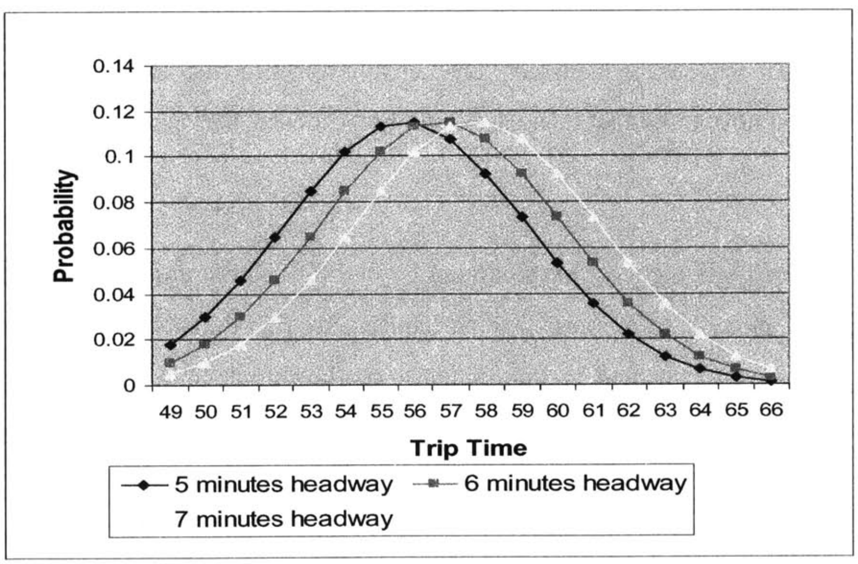


Figure 4-21 Westbound Trip Time Distributions with Different Headways

4.5. Operational Cost and Service Quality Estimation

The service quality and operational cost will be estimated with different schedule parameters based on the estimated trip time distribution in the scheduling process. In this section, I will discuss how to estimate the operational cost and service quality for route 77.

4.5.1. Operational Cost Estimation

The operational cost of route 77 during the AM peak is estimated applying the cost model derived in Chapter 3. According to the CTA 2001 estimated bus cost model stored in the excel file "2001Costs-EST00.xls", the scheduled cost during the AM peak (a period of 2 hours) per hour is:

$$\text{Scheduled Cost During AM peak} = (35.68*C + 0.78*d)*(60/h)*2$$

where C is the half cycle time (in hours), d is the route distance (in miles), and h is the headway (in minutes).

Late trips impose extra cost when the total work time of a driver is greater than the scheduled work time. So, it is estimated not by time period, but by day. In order to incorporate late trips cost in the operational cost during the AM peak, the late trips cost is estimated in two cases, one is the worst case in which all the late trips result in overtime and the other is the best case in which no late trip cost is incurred. The actually operational cost during the AM peak will be between the best cost and worst cost cases. In the best case, the operational cost is simply the scheduled cost.

The expected late trip cost is calculated by multiplying the unit cost associated with late trips, the expected minutes of lateness, and the probability that the late trip will cause the driver overtime. Therefore, the expected cost of a late trip can be expressed as:

$$\text{Expected cost of a late trip} = \alpha * C_a \int_C^\infty (T_i - C) f_t$$

Where α is the probability that the late trip will cause driver overtime, f_t is the trip time distribution, and C_a is the unit cost associated with late trips. In the worst case, α will be 1, which means that all the late trips are assumed to cause overtime. In the best case, α will be 0 which means that late trips do not impose additional costs. The expected late trip cost is mainly the driver's overtime wage. Since CTA bus operator's top hourly wage is $20.01, C_a is assumed to be 1.5 times this, \$ 30.02. Therefore, in the worst case, the expected cost of late trips during the AM peak will be:

$$\textit{Expected cost of late trip during AM peak} = 30.02 * \int_{C}^{\infty} (Ti - C) f_t * (60/h) * 2$$

4.5.2. Service Quality Estimation

The service quality on route 77 is measured in terms of speed and reliability. Passenger in-vehicle time reflects the speed of the service and passenger waiting time and schedule adherence reflect the reliability of the service. Crowding is considered as a constraint by using an upper bound on headway itself based on the maximum load standard to prevent over-crowding.

Passenger In-vehicle Time

The passenger in-vehicle time is estimated by the following equation:

$$\textit{In-vehicle time} = E(t) * \frac{\bar{l}}{d}$$

where E(t) is the expected trip time for the route, $\bar{l}$ is the average passenger trip length, and d is the route length. Unfortunately, since the data or average trip length for the route is not available, expected passenger in-vehicle time for route 77 cannot be estimated with the available data, and so half the expected trip time will be used as a proxy for the passenger in-vehicle time

Passenger Waiting Time

With the assumption that all passengers can board the first bus to arrive, the expected passenger waiting time E(w), for passengers who arrive randomly can be calculated from the equation:

$$E(w) = \frac{H}{2} + \frac{V(h)}{2H}$$

where H is the average departure headway at the stop and V(h) is the variance of the headway. I estimate passenger waiting time at one time point along the route with assumption that the passenger demand on that time point is highest and thus the waiting time at that time point represents the typical waiting time for route 77.

Schedule Adherence

I estimate the schedule adherence on route 77 with the on-time departure probability at the starting terminal, which is affected by the recovery time and on-time arrival probability at the last time points, which is affected by schedule time. Here it is assumed that a vehicle is "on time" if it is no more than 5 minutes later than the schedule time.

Crowding

The crowding level is used to determine the upper bound on headway in this case study. The crowding level is measured by the maximum load during the peak hour. According to the Chicago Transit Authority Service Standard, the average number of passengers per bus should not exceed 60 passengers at any location. Headways that result in passenger loads exceeding this standard (60 passengers) at the maximum load point will not be considered feasible.

4.6. Applying Scheduling Process

In this section, I apply the schedule parameter setting process to the CTA route 77. The process of setting schedule parameters proposed in Section 3.7 is:

1. Develop an upper bound on headway based on the maximum crowding standard and a lower bound on headway based on Revenue/Cost ratio or Benefit/Cost ratio.
2. Service frequency setting: According to the current general service standards, the initial frequency of the route will be chosen.
3. Minimum schedule time setting: Minimum schedule time setting: The minimum schedule time at the last time point will be set to the schedule time which makes 20% of trips early at that time point. The schedule time for the last segment (from the last time point to the destination) is the average last segment trip time. Thus, the minimum schedule time will

be the sum of the minimum schedule time at the last time point and the average segment trip time.

4. Trip time distribution estimation: Trip time distribution with the given service frequency and the minimum scheduled time will be estimated.
5. Half cycle time setting: The half cycle time necessary to achieve 85%, 90%, 95%, and 97% of on time departure probability will be estimated from the cumulative trip time distribution. The recovery time is then set to the difference between the half cycle time and schedule time in this process.
6. Operational cost and service quality estimation: Estimate the operational cost and service quality of the given combination of headway, schedule time, and half cycle time.
7. Schedule time change: Increase the schedule time and repeat steps 4 to 6 until 80% of trips can arrive earlier than the schedule time.
8. Service frequency change: Increase or decrease the service frequency and repeat steps 3 to 7 of the process until it reaches the upper bound and lower bound on headway. .
9. Tradeoffs between the operational cost and service quality: Plot the operational costs and service qualities with different combinations of service frequency, scheduled time and recovery time.

First of all the upper bound on headway is set according to the crowding level. The passenger arrival rate during the AM peak, from 7:00 to 8:00 AM is 15 passengers/minute for the eastbound direction and 12 passengers/minute for the westbound. This means that the average number of passengers boarding per bus eastbound is 75 passengers/trip and westbound is 72 passenger/trip with current headways. According to the CTA load check data, from 7:00 to 8:00 AM, Central Park has the highest average load, which is 50 passengers per bus. Thus we can make the assumption that the average passenger load at the peak location is about 2/3 of the number of passengers boarding per bus. Based on this assumption, the maximum headway eastbound is 6 minutes and the maximum headway westbound is 7 minutes. The lower bound on headway is set according to productivity measures such as Revenue/Cost ratio or Benefit/Cost ratio and headways smaller than 4 minutes are not acceptable since it requires too much costs.

After developing the upper and lower bounds on headway, a base case is established with the current headway and minimum schedule time and operational cost and service quality with different cycle times are estimated. In step 7, schedule time is increased by 2 minutes with the same frequency and steps 4 to 6 are repeated. The spreadsheet-based model to estimate the trip time distribution with different schedule times is used to generate the trip time distribution when the schedule time changes. The same assumptions made in Section 4.4.1 will be used to apply this model.

In step 8, service frequency is changed and steps 3 to 7 are repeated. The unconstrained trip time distribution for the changed headways derived in Section 4.4.2 will be used. When all the operational cost and service with different schedule times and frequencies are estimated according to the process, finally the tradeoffs between operational cost and service quality are plotted and the optimal schedule parameters are determined.

Headway		**Case 1. Current Headway**			
Schedule Time		Minimum Schedule Time	Minimum Schedule Time + 2 minutes	Minimum Schedule Time + 4 minutes	Minimum Schedule Time + 6 minutes
On Time Departure Probability	85%	Case 1.1.1	Case 1.2.1	Case 1.3.1	Case 1.4.1
	90%	Case 1.1.2	Case 1.2.2	Case 1.3.2	Case 1.4.2
	95%	Case 1.1.3	Case 1.2.3	Case 1.3.3	Case 1.4.3
	97%	Case 1.1.4	Case 1.2.4	Case 1.3.4	Case 1.4.4
Headway		**Case 2. Increased Headway**			
Schedule Time		Minimum Schedule Time	Minimum Schedule Time + 2 minutes	Minimum Schedule Time + 4 minutes	Minimum Schedule Time + 6 minutes
On Time Departure Probability	85%	Case 2.1.1	Case 2.2.1	Case 2.3.1	Case 2.4.1
	90%	Case 2.1.2	Case 2.2.2	Case 2.3.2	Case 2.4.2
	95%	Case 2.1.3	Case 2.2.3	Case 2.3.3	Case 2.4.3
	97%	Case 2.1.4	Case 2.2.4	Case 2.3.4	Case 2.4.4
Headway		**Case 3. Decreased Headway**			
Schedule Time		Minimum Schedule Time	Minimum Schedule Time + 2 minutes	Minimum Schedule Time + 4 minutes	Minimum Schedule Time + 6 minutes
On Time Departure Probability	85%	Case 3.1.1	Case 3.2.1	Case 3.3.1	Case 3.4.1
	90%	Case 3.1.2	Case 3.2.2	Case 3.3.2	Case 3.4.2
	95%	Case 3.1.3	Case 3.2.3	Case 3.3.3	Case 3.4.3
	97%	Case 3.1.4	Case 3.2.4	Case 3.3.4	Case 3.4.4

Table 4-11 Assessment Cases

Several cases with variations in headway, schedule time, and recovery time were tested by applying the scheduling process as shown in Table 4-11. The initial schedule time is set to minimum schedule time and then it is increased in increments of 2 minutes until 80% of trips are expected to be earlier than the schedule trip time. The on time departure probability means the probability that a vehicle can start its next trip on time. Therefore, it determines the half cycle time and recovery time of the route. Here, recovery times which are less than the minimum recovery time, 5 minutes, are increased to the minimum recovery time. In the next sections, I will estimate the trip time distribution, schedule parameters, operational cost and service quality for each of these cases.

4.7. Case Evaluations

In this section, I will show the relationships between schedule parameters, service quality and operational cost for route 77 during the AM peak. I will also discuss the tradeoffs between operational cost and service quality, which transit agency staff should consider when setting schedule parameters.

4.7.1. Case 1: Current Headway

The trip time distributions and schedule parameters with the current headways are estimated in Section 4.4.1. The schedule times and recovery times are summarized in Table 4-12 and the operational costs and service qualities with different schedule parameters are summarized in Table 4-13.

Eastbound

Schedule Trip Time		60.5		62.5		64.5		66.5	
		Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time
On Time Departure Probability	85%	7.5	68	6	68.5	5*	69.5	-	-
	90%	8.5	69	7	69.5	5.5	70	-	-
	95%	10	70.5	8	70.5	6.5	71	5*	71.5
	97%~	11	71.5	9	71.5	7.5	72	5.5	72

Westbound

Schedule Trip Time		53		55		57		59	
		Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time
On Time Departure Probability	85%	7	60	5	60	-	-	-	-
	90%	8	61	6	61	-	-	-	-
	95%	9	62	7	62	5	62	-	-
	97%~	10	63	8	63	6	63	5*	64

* Minimum recovery time used

Table 4-12 Schedule Parameters in minutes (Current Headway)

Case 1. Current Headway (East: 5 mins, West: 6 mins)									
Schedule Trip Time		EB 60.5	WB 53	EB 62.5	WB 55	EB 64.5	WB 57	EB 66.5	WB 59
Passenger In-vehicle Time		30.6		30.9		31.3		32.0	
On Time Arrival Probability at the Last Timepoint		0.70		0.87		0.96		0.99	
Passenger Waiting Time		3.7		3.4		3.2		3.0	
		Operational Cost (dollars) - Best Case							
On Time Departure Probability at the Terminal	85%	1007		1010		1029		-	
	90%	1020		1023		1033		-	
	95%	1036		1036		1040		1055	
	97%~	1050		1050		1053		1059	
		Operational Cost (dollars) - Worst Case							
On Time Departure Probability at the Terminal	85%	1014		1015		1032		-	
	90%	1024		1026		1035		-	
	95%	1038		1038		1042		1056	
	97%~	1050		1050		1054		1059	

Table 4-13 Operational Cost and Service Quality with Current Headway

- **Relationships between service quality and schedule time**

As the schedule time is increased, the service quality measures improve except for passenger in-vehicle time. The passenger waiting time is decreased by about 15 seconds for each 2-minute increase in schedule time. This is because the arrival headway at each time point becomes more even as the schedule time increases with the schedule based holding strategy. The passenger in-vehicle time increases due to the increases in the expected trip time as the schedule time increases. The on time arrival probability improves due to more slack time to catch up with the schedule as the schedule time increases.

Figure 4-22 shows the relationships between the schedule time, the on-time arrival probability and the passenger in-vehicle time. On time arrival probability increases more sharply between the 113.5 and 117.5 minute combined schedule times while the in-vehicle time increases only modestly over this range of schedule time. Beyond a schedule time of 121.5 minutes the in-vehicle time increases more sharply with smaller improvements in the on time arrival probability. This confirms that too much schedule time will result in worse overall service quality by increasing the passenger in-vehicle time more than the benefit gained from reducing the passenger waiting time and improving the on time performance.

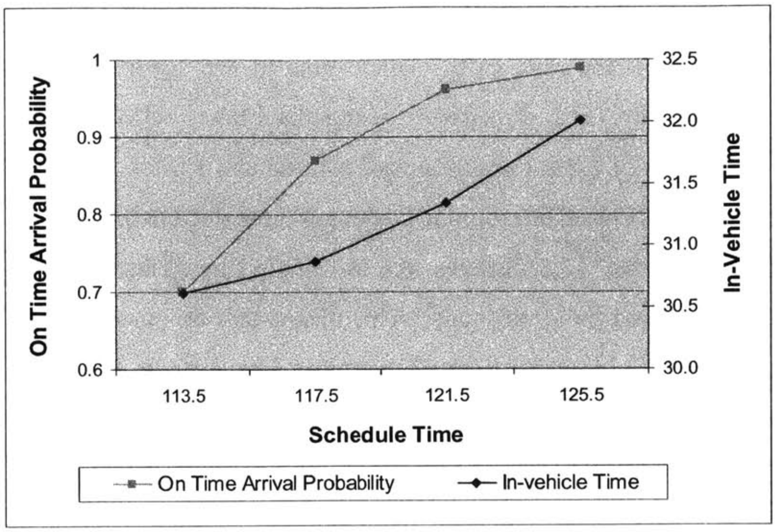


Figure 4-22 Relationship between Schedule Time, On Time Arrival Probability and In-vehicle Time

- **Tradeoff between passenger in-vehicle time and passenger waiting time**

There is a tradeoff between the passenger in-vehicle time and waiting time since the in-vehicle time increases as the schedule time increases while the waiting time decreases. Therefore, we should select the schedule time considering the tradeoff between them. As shown in Figure 4-23, the in-vehicle time increases more steeply than the waiting time decreases in general. However, this does not mean that increasing the schedule time always increases "weighted" passenger time since passengers typically value waiting time higher than in-vehicle time. This difference in value of waiting versus in-vehicle time should be recognized in selecting the schedule time.

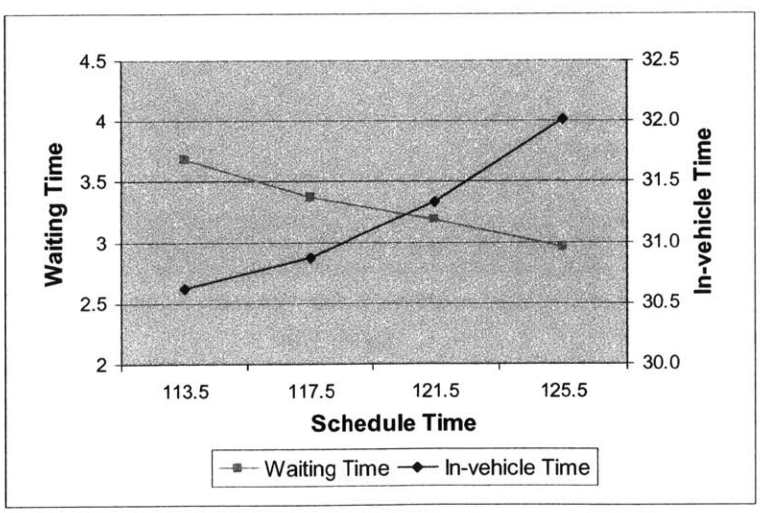


Figure 4-23 Tradeoff between In-vehicle Time and Waiting Time

Table 4-14 shows the changes in the passenger in-vehicle time and waiting time for different schedule times. If the ratio of in-vehicle time to waiting time is less than the critical ratio that the transit agency uses, it is worth using the higher schedule time. Horowitz and Thomson suggested a ratio of 2.0 for unproductive waiting and 1.0 for productive waiting in their document entitled "Evaluation of Intermodal Passenger Transfer Facilities". When the schedule time increases from 113.5 to 117.5 minutes, the in-vehicle time is increased by 16 seconds and the waiting time is decreased by 19 seconds. This means that this increase in the schedule time results in passenger time saving regardless of the ratio. However, it is not worth increasing the schedule time to more than 117.5 minutes unless the transit agency values the passenger waiting time at more than 2.5 times the in-vehicle time.

Schedule Time Change	113.5-117.5	117.5-121.5	121.5-125.5
Increase in In-vehicle Time (seconds)	15.5	27.7	40.5
Decrease in Waiting Time (seconds)	18.5	11.2	13.8
Ratio of In-vehicle Time to Waiting Time	0.8	2.5	2.9

Table 4-14 In-vehicle Time and Waiting Time Changes with Current Headway

- **Relationships between operational cost and cycle time**

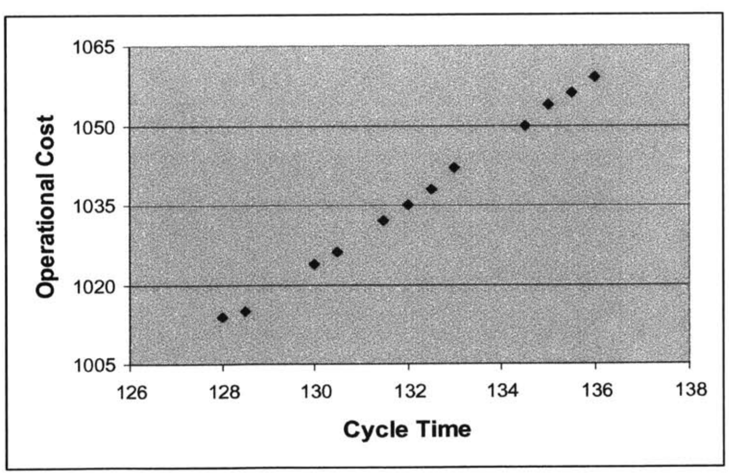


Figure 4-24 Relationship between Cycle Time and Operational Cost

As shown in Figure 4-24, the operational cost increases as the cycle time increases. It is shown in Table 4-13 that the operational cost increases as the on time departure probability increases given a schedule time and the operational cost is the same if the cycle time is the same though schedule times are different. When the schedule time is long and thus the on time arrival probability is high, the minimum recovery time is more likely to be binding. The minimum recovery time results in a longer cycle time than is needed based on the desired on time departure probability and thus requires greater operational cost increases. For example, the operational cost is increased by $14 if the schedule time is increased from 121.5 to 125.5 while it increases by just $4 if the schedule time is increased from 117.5 minutes to 121.5 minutes for 95 percent on time departure probability.

- **Late trip cost**

In all the cases examined the lateness cost represents less than 1% of the total operational cost. This is because the cycle time is set to achieve a high probability of on time departure meaning there is a low probability that any vehicle is late. As the on time arrival and departure probabilities are improved, the late trip cost is reduced. Also, the minimum recovery time makes the on time departure probability even higher than 97% for long schedule times and so there are almost no late trips.

- **Recommended schedule parameters for current headway**

As mentioned above, too much schedule time results in high operational cost due to the minimum recovery time and long in-vehicle time while it does not improve the other aspects of service quality significantly. Therefore, we should find the schedule time that produce higher marginal benefit than the increase in operational cost.

First of all, 113.5 minutes schedule time and 117.5 minutes schedule time have very similar operational cost since they have similar cycle times. However, the passenger time is reduced and the on time arrival probability is significantly improved at a schedule time of 117.5 minutes compared to 113.5 minutes. After 117.5 minutes schedule time, the passenger time starts to increase since the ratio of in-vehicle time to waiting time is usually smaller than 2.5 and the operational cost also starts to increase. This shows that the high on time arrival probability based on the long schedule time increases the operational cost without any real increase in passenger benefits. Therefore, under the current headway, a schedule time of 117.5 minutes is recommended.

In the cost model, the cost incurred when adding one more bus on the route is not considered. However, in reality, adding one more bus significantly increases the operational cost. Therefore, the schedule parameters should be determined based on the point where the required number of buses increases. The number of buses needed to run the trips with given on time departure probability and schedule time is summarized in Table 4-15.

Schedule Trip Time		113.5	117.5	121.5	126.5
On Time Departure Probability at the Terminal	85%	24	24	25	-
	90%	25	25	25	-
	95%	26	26	26	26
	97%~	26	26	26	26

Table 4-15 Number of buses needed with Current Headway

When the schedule time is 117.5 minutes, the number of buses increases by one when the on time departure probability is improved from 85% to 90% and from 90% to 95%. Therefore, the recommended on time departure probability is 85% which does not require an additional vehicle under the current headway. The recommended schedule parameters under the current headway is 62.5 minutes schedule trip time and 6 minutes recovery time eastbound and 55 minutes schedule trip time and 5 minutes recovery time westbound.

- **Comparison of recommended schedule with current schedule**

The current and recommended schedule parameters, estimated operational costs and service qualities are summarized in Table 4-16. During the AM peak, the CTA provides service between Cumberland on Belmont and Diversey on Lake Shore Drive. Since, this case study only considers the route segment between Cumberland and Halsted on Belmont, the current recovery time of the simplified route is assumed to be the same proportion of current recovery time as the proportion of simplified and actual route lengths.

First of all, the current schedule appears to have too much recovery times in both directions which should produce very high on time departure probability. It also results in too much operational cost. The recommended schedule reduces the operational cost by $65, or 6% by reducing unnecessary recovery times. 26 vehicles are needed with the current schedule while 24 vehicles are needed with recommended schedule. Therefore, the reduction in the number of vehicle should save real operational cost.

As a result of the schedule-based holding strategy, the on time arrival probability and passenger waiting time are improved even though the recommended schedule time is reduced. This shows that schedule-based holding makes the overall operations more reliable. However, it increases the passenger in-vehicle time.

	Current Schedule		Recommended Schedule	
	Eastbound	Westbound	Eastbound	Westbound
Schedule Trip Time	65	55	62.5	55
Recovery Time	10	9	6	5
On Time Departure Probability	97%~	97%~	85%	85%
Cycle Time	139		128.5	
Passenger In-vehicle Time	30.3		30.9	
On Time Arrival Probability at the Last Timepoint	0.53		0.87	
Passenger Waiting Time	3.6		3.4	
Operational Cost	1080		1015	

Table 4-16 Current Schedule Parameters, Service Quality, and Operational Cost

Though the on time departure probability and passenger in-vehicle time of the current schedule are better than the recommended schedule, a 6% operational cost saving can be achieved and the on time arrival probability and passenger waiting time can be improved significantly with the recommended schedule. This comparison clearly shows that applying the proposed scheduling process and the schedule-based holding can save operational cost by reducing unnecessary recovery time at the same time as improving overall service quality.

4.7.2. Case 2: Increased Headway

The unconstrained trip time distribution with increased headway follows a normal distribution having a mean of 65.5 minutes and a standard deviation of 4.0 minutes eastbound, and a mean of 57.7 minutes and a standard deviation of 3.5 minutes westbound. The trip time distributions with different schedule trip times are shown in Figures 4-25 and 4-26. Table 4-17 summarizes the schedule times and recovery times for the increased headways and Table 4-18 summarizes the operational cost and service quality.

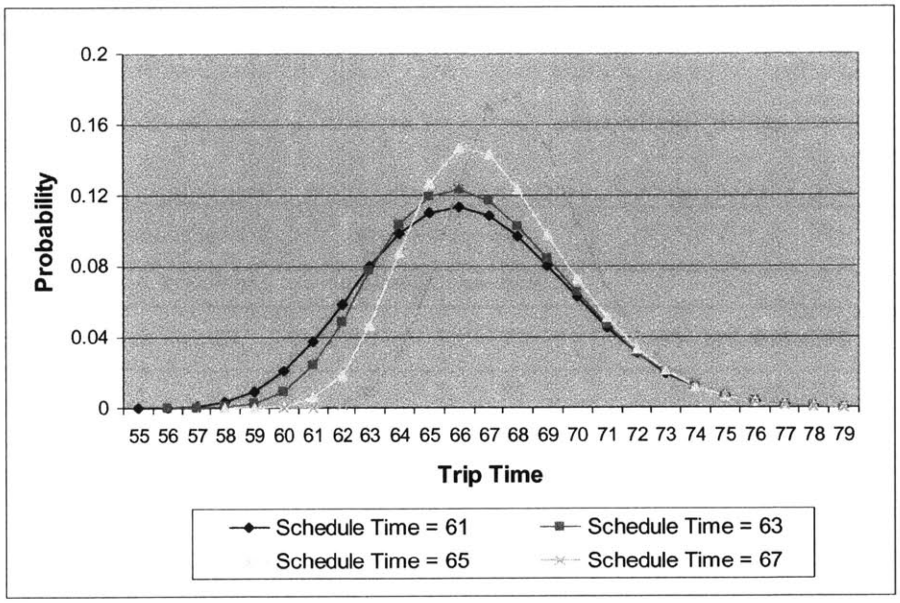


Figure 4-25 Eastbound Trip Time Distributions (6 minutes headway)

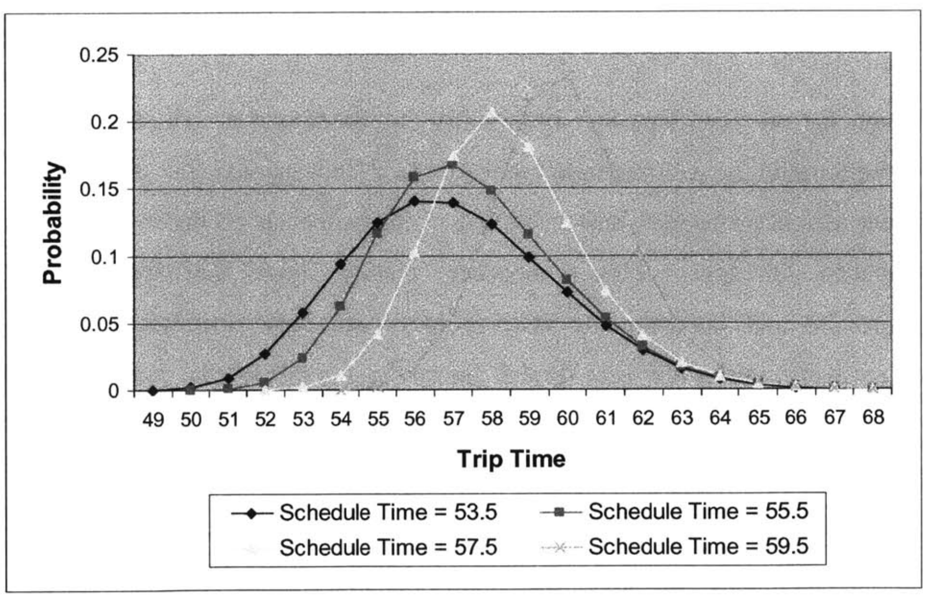


Figure 4-26 Westbound Trip Time Distributions (7 minutes headway)

Eastbound

Schedule Trip Time		61		63		65		67	
		Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time
On Time Departure Probability	85%	8.5	69.5	6.5	69.5	5	70	-	-
	90%	9.5	70.5	7.5	70.5	6	71	-	-
	95%	10.5	71.5	8.5	71.5	7	72	5	72
	97%~	11.5	72.5	9.5	72.5	8	73	6	73

Westbound

Schedule Trip Time		53.5		55.5		57.5		59.5	
		Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time
On Time Departure Probability	85%	6	59.5	-	-	-	-	-	-
	90%	6.5	60	5	60.5	-	-	-	-
	95%	7	60.5	6	61.5	-	-	-	-
	97%~	7.5	61	6.5	62	5	62.5	5*	64.5

* Minimum recovery time used

Table 4-17 Schedule Parameters in minutes (Increased headway)

Case 2. Increased Headway (East: 6 mins, West: 7 mins)									
Schedule Trip Time		EB 61	WB 53.5	EB 63	WB 55.5	EB 65	WB 57.5	EB 67	WB 59.5
Passenger In-vehicle Time		30.8		31.1		31.6		32.2	
On Time Arrival Probability at the Last Timepoint		0.6		0.83		0.94		0.98	
Passenger Waiting Time		4.1		3.8		3.6		3.5	
		Operational Cost (dollars) - Best Case							
On Time Departure Probability at the Terminal	85%	856		861		874		-	
	90%	864		867		880		-	
	95%	873		878		886		896	
	97%	881		886		892		902	
		Operational Cost (dollars) - Worst Case							
On Time Departure Probability at the Terminal	85%	859		864		877		-	
	90%	866		869		882		-	
	95%	874		880		887		897	
	97%	882		888		892		902	

Table 4-18 Operational Cost and Service Quality with Increased Headway

The same relationships between the service quality and the schedule time and between the operational cost and the cycle time, discussed in the previous case, also exist in this case. The changes in the passenger in-vehicle time and waiting time based on the schedule time changes are summarized in Table 4-19. When the schedule time is increased from 114.5 to 118.5 minutes, the in-vehicle time increases by 16 seconds and the waiting time decreases by 20 seconds. This means that this increase in the schedule time is clearly beneficial to the passengers. If the critical ratio that transit agency uses is 1.25, which is conservative value, 118.5 minutes schedule time can save 240 passenger-minutes compared with 114.5 minutes schedule time. However, it is not worth increasing the schedule time beyond 118.5 minutes since the critical ratio would have to be greater than 2.5, which is probability at about the upper bound.

Schedule Time Change	114.5-118.5	118.5-122.5	122.5-126.5
Increase in In-vehicle Time (seconds)	15.7	27.6	40.1
Decrease in Waiting Time (seconds)	19.8	11.1	9.4
Ratio of In-vehicle Time to Waiting Time	0.8	2.5	4.3

Table 4-19 In-vehicle Time and Waiting Time Changes with Increased Headway

- **Recommended schedule parameters for increased headway**

The passenger time is reduced and the on time arrival probability is significantly improved at a schedule time of 118.5 minutes compared to 114.5 minutes. However, after 118.5 minutes schedule time, the weighted passenger time increases. The operational cost increases by about $5 while 240 passenger-minutes is saved with 118.5 minutes schedule time compared to 114.5 minutes schedule time. According to a survey by the Resource Systems Group, Inc., for the Chicago Department of Transportation, done in September of 1999, CTA passengers value their travel time at about $0.10/minute. With this value of travel time, the additional operational cost needed for the longer schedule time can be justified by the reduced passenger time. Therefore, under the increased headway, 118.5 minutes schedule time is recommended.

Schedule Trip Time		114.5	118.5	122.5	126.5
On Time Departure Probability at the Terminal	85%	21	21	21	-
	90%	21	21	21	-
	95%	21	21	21	22
	97%~	22	22	22	23

Table 4-20 Number of buses needed with Increased Headway

The number of buses needed with the increased headway given on time departure probability and schedule time is summarized in Table 4-20. When the schedule time is 118.5

minutes, one more bus is needed to improve the on time departure probability from 95% to 97%. Therefore, the recommended on time departure probability is 95% which does not require the additional vehicle. The recommended schedule parameters are 63 minutes schedule trip time and 8.5 minutes recovery time eastbound and 55 minutes schedule trip time and 6 minutes recovery time westbound.

4.7.3. Case 3: Decreased Headway

The eastbound unconstrained trip time distribution with increased headway follows a normal distribution having a mean of 63.5 minutes and a standard deviation of 4.0 and the westbound having a mean of 55.7 minutes and a standard deviation of 3.5 minutes westbound. The trip time distributions with different schedule trip times are shown in Figures 4-27 and 4-28. Table 4-21 summarizes the schedule times and recovery times and Table 4-22 summarizes the operational cost and service quality for the decreased headway.

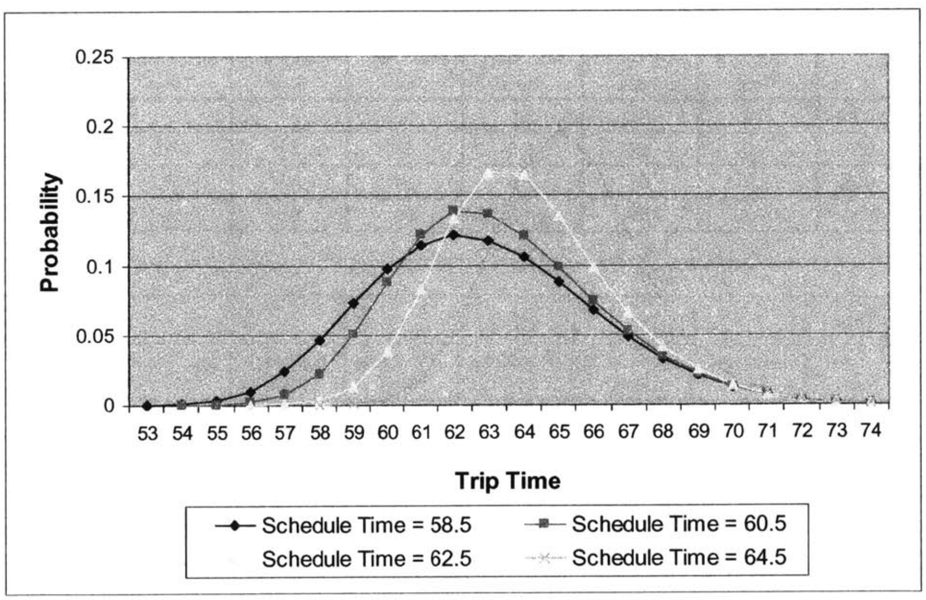


Figure 4-27 Eastbound Trip Time Distribution (4 minutes headway)

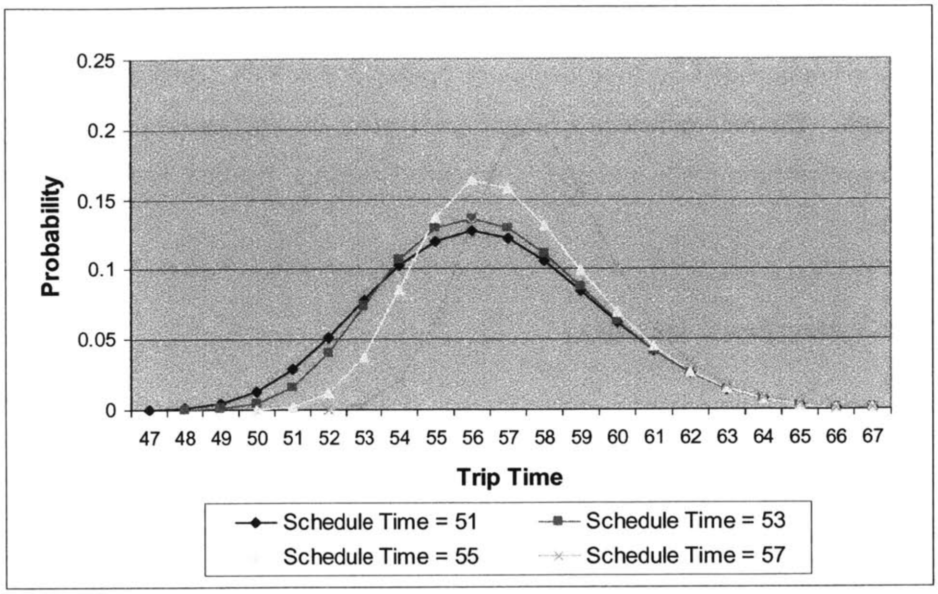


Figure 4-28 Westbound Trip Time Distributions (5 minutes headway)

Eastbound

Schedule Trip Time		58.5		60.5		62.5		64.5	
		Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time
On Time Departure Probability	85%	7.5	66	5.5	66	-	-	-	-
	90%	8.5	67	6.5	67	5*	67.5	-	-
	95%	9.5	68	7.5	68	5.5	68	-	-
	97%~	10.5	69	8.5	69	6.5	69	5	69.5

Westbound

Schedule Trip Time		51		53		55		57	
		Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time	Recovery Time	Half Cycle Time
On Time Departure Probability	85%	9	59	7	59	-	-	-	-
	90%	10	60	8	60	5	60	-	-
	95%	11	61	9	61	6	61	-	-
	97%~	12	62	10	62	7	62	5	62

* Minimum recovery time used

Table 4-21 Schedule Parameters in minutes (Decreased headway)

Case 3. Decreased Headway (East: 4 mins, West: 5 mins)									
Schedule Trip Time		EB 58.5	WB 51	EB 60.5	WB 53	EB 62.5	WB 55	EB 64.5	WB 57
Passenger In-vehicle Time		29.7		29.9		30.3		31.0	
On Time Arrival Probability at the Last Timepoint		0.58		0.80		0.93		0.98	
Passenger Waiting Time		3.5		3.0		2.8		2.5	
		Operational Cost (dollars) - Best Case							
On Time Departure Probability at the Terminal	85%	1212		1212		-		-	
	90%	1228		1228		1232		-	
	95%	1244		1244		1244		-	
	97%~	1260		1260		1260		1264	
		Operational Cost (dollars) - Worst Case							
On Time Departure Probability at the Terminal	85%	1219		1219		-		-	
	90%	1232		1232		1236		-	
	95%	1246		1246		1246		-	
	97%~	1261		1261		1261		1265	

Table 4-22 Operational Cost and Service Quality with Decreased Headway

The service quality except for passenger in-vehicle time improves as the schedule time is increased and the operational cost increases as the cycle time is increased as mentioned earlier.

- **Selection of ratio of in-vehicle time and waiting time**

Schedule Time Change	109.5-113.5	113.5-117.5	117.5-121.5
Increase in In-vehicle Time (seconds)	13.2	24.1	37.2
Decrease in Waiting Time (seconds)	26.6	15.6	14.9
Ratio of In-vehicle Time to Waiting Time	0.5	1.5	2.5

Table 4-23 In-vehicle Time and Waiting Time Changes with Decreased Headway

The changes in the passenger in-vehicle time and waiting time based on the schedule time changes are summarized in Table 4-23. When the schedule time increases from 109.5 to 113.5 minutes, the in-vehicle time increases by 13 seconds and the waiting time decreases by 27 seconds. This means that this increase in the schedule time clearly improves passenger service. If the waiting time ratio that the agency uses is greater than 1.5, it is worth increasing the schedule time to 117.5 minutes. However, if the transit agency uses the conservative waiting time ratio, 1.25, the schedule time is recommended at 113.5 minutes. This confirms that the selection of the ratio of in-vehicle time and waiting time affects the decision on the schedule time.

- **Recommended schedule parameters for decreased headway**

Schedule time of 109.5 and 113.5 minutes have the same operational cost since they have the same cycle times for all on time departure probabilities. However, the passenger time is reduced and the on time arrival probability is significantly improved at a schedule time of 113.5 minutes schedule time compared with 109.5 minutes schedule time. The operational costs when the schedule times are 113.5 minutes and 117.5 minutes are the same except for 90% on time departure probability. 117.5 minutes is recommended as the schedule time with the decreased headway since at 117.5 minutes schedule time the on time arrival probability improves significantly and also the increase in the passenger in-vehicle time can be compensated for by the reduction in the passenger waiting time with a waiting time ratio, 1.5, which is in the reasonable range.

The number of buses needed for each combination of schedule parameters is summarized in Table 4-24. When the schedule time is 117.5 minutes, the number of buses increases by one when the on time departure probability is improved from 90% to 95% and from 95% to 97%. Therefore, the recommended on time departure probability is 90% which does not require an additional vehicle. Accordingly, the recommended schedule parameters is 62.5 minutes schedule trip time and 5 minutes recovery time eastbound and 55 minutes schedule trip time and 5 minutes recovery time westbound.

Schedule Trip Time		109.5	113.5	117.5	121.5
On Time Departure Probability at the Terminal	85%	29	29	-	-
	90%	29	29	29	-
	95%	30	30	30	-
	97%~	31	31	31	31

Table 4-24 Number of buses needed with Decreased Headway

4.7.4. Headway Recommendation

So far I have discussed the issues in setting the schedule time, cycle time and recovery time given a headway. However, the decision on the headway is critical since it is the principal determinant of the operational cost. Figure 4-29 shows the relationship between the operational cost and the schedule parameters. In this figure, each line indicates a different schedule headway. As described in Chapter 3, the operational cost steadily increases with the cycle time given a headway, and the operational cost jumps as the headway increases given a cycle time.

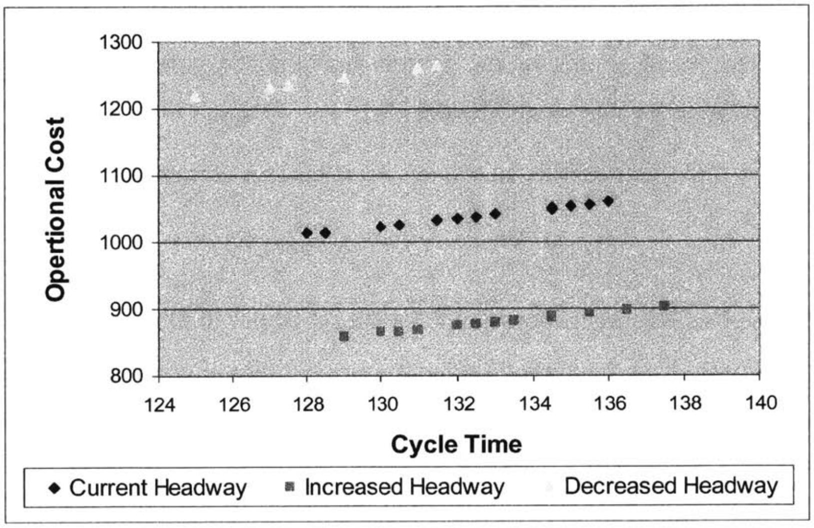


Figure 4-29 Relationship between Operational Cost and Schedule Parameters

Table 4-25 summarizes the operational costs and the service quality with different headways. The shorter headway has the greatest operational cost and the best service quality. By increasing mean scheduled headways by one minute from the current headways, the passenger in-vehicle time increases by 13 seconds and the passenger waiting time increases by 25 second, for a total increase of 1370 passenger-minutes to produce $135 operational cost savings. By decreasing scheduled headways by one minute from the current headway, the passenger in-vehicle time decreases by 31 seconds and the passenger waiting time decreases by 35 seconds, for a total reduction of 2250 passenger-minutes at an additional $221 operational cost. If it is assumed that the passenger in-vehicle time value is 10 cents per minute and the waiting time ratio is 1.5, the additional costs (or cost savings) are just offset by benefits gained (or lost).

Headway	EB	WB	EB	WB	EB	WB
	4	5	5	6	6	7
Operational Cost	1236		1015		880	
Passenger In-vehicle Time	30.3		30.9		31.1	
Passenger Waiting Time	2.8		3.4		3.8	

Table 4-25 Operational Cost and Service Quality with Different Headways

The decision on headway cannot be made at the route level since the budget constraint exists at the system level. Even though it is clear that the service quality of a route is improved by providing more frequent service, the transit agency cannot assign more vehicles to that route if there is another route that produces higher benefits than the route. Therefore, after the proposed scheduling is applied to all routes in the system and the marginal benefits of all routes are compared, the headway of a route should be decided.

4.7.5. Discussion

The proposed scheduling process enables the scheduler to explore different combinations of the schedule parameters and estimate the resulting operational cost and service quality. Thus the tradeoff between the operational cost and the service quality or the tradeoff between the passenger in-vehicle time and the passenger waiting time can be considered when setting the schedule parameters. However, the real decisions on the schedule parameters are made by the transit agency's staff based on their own judgment on the passenger time value or the ratio of passenger in-vehicle time value to waiting time value not by the scheduling process automatically. In this section, I will discuss the factors that affect the decision on the schedule parameters.

- **Passenger Travel Time Value**

Passenger time value is used to translate the benefit gained from time saving to a monetary value. Thus the passenger travel time value that the agency uses will affect the decision on the schedule parameters based on the tradeoff between the operational cost and service quality. Too high a value will result in an unnecessary increase in operational costs and too low a value will result in poor service quality. Therefore, the choice of passenger travel time value should be made prudently based on credible passenger surveys which can be used to estimate the real value.

- **Ratio of Passenger In-vehicle Time to Waiting Time**

A second important element that affects the decision on the schedule parameters is the selection of the ratio of passenger in-vehicle time to waiting time. The waiting time ratio determines the tradeoff between passenger in-vehicle time and waiting time as well as the tradeoff between operational cost and overall service quality. This value ranges between 1 and 2 according to previous research. This ratio should be decided based on passenger perceptions and the route characteristics.

- **Integer Number of Buses**

The other critical factor which affects the decision on the schedule parameters is the number of bus required for the operations. It requires significant costs to add one more bus to a route in the peak period. Moreover, the number of buses is likely to be a constraint rather than a decision variable. Therefore, the schedule parameter decisions are usually made in terms of when an additional bus is required. Since the costs of different numbers of buses are not considered in the cost model used in this case study, the number of buses are just used to decide the cycle time in this case study. However, if this factor is included in the cost model, it may change the operational cost estimates and thus also the decisions on the schedule parameters.

- **Budget Constraint**

In reality, the total operational cost for the transit agency is constrained by the budget available. It may be that the transit agency cannot provide more frequent service or increase the schedule time or cycle time due to the budget constraint even though it is clear that it will improve the service quality. Therefore, the available budget impacts the decision on the schedule parameters by binding the operational cost. The budget constraint exists at the system level of course, and thus route and time period scheduling decisions are linked though this system level constraint as described by Furth and Koutsopoulos (1980, 1983).

Chapter 5. Summary and Conclusions

This chapter summarizes the results of the research in developing the relationships between schedule parameters, operational cost and service quality, and the application to the CTA bus route 77. It concludes with suggestions for future research.

5.1. Summary

Developing an operating plan involves balancing different objectives for the passengers and the agency. Passengers are interested in high service quality and transit agencies are interested in low operational cost while maintaining a certain level of service quality. Since the operational cost and service quality are largely determined by the schedule parameters, the decision on the schedule parameters should be made with a full understanding of the passenger and agency objectives and the relationships between the schedule parameters, operational cost and service quality. To determine the schedule parameters which best satisfy the objectives of both the passengers and the transit agency, different combinations of schedule parameters should be explored and the operational cost and service quality of the combinations of schedule parameters should be estimated.

In order to develop the relationships between schedule parameters, operational cost and service quality, an analytical model was developed to estimate the trip time distribution with different schedule parameters for a simplified bus route incorporating a schedule-based holding strategy at time points. The model showed that increasing the schedule time and number of time points increases the mean of the trip time distribution while decreasing its variability. It also showed that the critical decisions, which affect the shape of the trip time distribution, are the location and schedule time at the last time point. Second, a dwell time model to assess the impact of headway change on the trip time distribution was built. Dwell time models can be either at the stop level or at the aggregate trip level depending on the data availability. The principle variables which affect the dwell time are numbers of passengers boarding and alighting. The dwell time model showed that the trip time distribution can be affected by the vehicle headway since the passenger demand which is controlled by the vehicle headway determines the dwell time.

The impacts of changes in the trip time distribution caused by the change of one scheduled parameter on the other scheduled parameters were explored. The relationship between schedule time and recovery time was presented through an example. From the example, it is shown that the recovery time is determined by the on-time departure probability at the terminal and schedule time. The relationship between recovery time and headway distribution were developed from the relationship between departure time at the starting terminal and vehicle arrival time at the ending terminal. The headway distribution becomes tighter as the recovery time increases.

The relationships between the operational cost and the schedule parameters were derived by developing a cost model, which is also a function of the schedule parameters. The operational cost consists of the scheduled cost and the expected cost of late trips. According to the derived cost model, as the schedule time increases the scheduled cost will increase, while the late trip cost will decrease since the probability that the total time will exceed the driver's work time will decrease. As the headway increases, the scheduled cost decreases, while the late trip cost will increase since the trip time will increase due to longer dwell time and thus the probability of late departure will increase.

The impacts of the schedule parameters on service quality were assessed in terms of the in-vehicle time, passenger waiting time, schedule adherence and crowding level. The in-vehicle time is affected by the schedule time and headway, the passenger waiting time and crowding level are affected by the headway and recovery time, and the schedule adherence is affected by the schedule time and recovery time.

Finally, a scheduling process incorporating the relationships between schedule parameters, operational cost and service quality was proposed. The process allows a scheduler to estimate the operational cost and service quality of different combinations of schedule parameters. This makes it possible to find a better combination of schedule parameters, which meet the agency's objective by considering the tradeoff between the operational cost and service quality.

The relationships and the scheduling process were developed and applied to the CTA bus route 77. The trip time distributions were generated using the analytical model to estimate the trip time distribution with different schedule times and the dwell time model of route 77 with different schedule time and headway. Then the half cycle time was determined based on the trip time distribution and desired on-time departure probability at the terminal. The operational cost and service quality of different combinations of schedule parameters were estimated. The operational cost was estimated in two cases, one is the worst case in which all late trips resulted in overtime and the other is the best case in which no late trip cost was incurred. In all the cases, the lateness cost represented less than 1% of the total operational cost due to the specified high on time departure probability.

As the schedule time was increased, the trip time distribution had a longer mean and smaller variance as described in the theoretical analysis. As the headway increased (decreased) by one minute, the mean of the unconstrained trip time distribution increased (decreased) by one minutes based on the dwell time changes. As the schedule time increased, less recovery time was needed to maintain the same on time departure probability or to improve the on time departure probability to the next level.

As the schedule time increased given a headway, the service quality, except for the passenger in-vehicle time, improved. The passenger waiting time improved due to smaller headway variance at each time point and on time arrival probability improved due to more slack time to catch up with the schedule with the schedule-based holding. The passenger in-vehicle time increased due to the increases in the expected trip time as the schedule time increases. From the relationships between schedule time and service quality, it was shown that too much schedule time will result in worse overall service quality by increasing in-vehicle time more than the benefit gained from reducing waiting time and improving on time performance. It was shown that the operational cost increased as the cycle time is increased given a headway. As the headway decreased, the service quality improved and the operational cost increased.

The tradeoffs existing in the scheduling process were presented through the case study. First of all, there was a tradeoff between the operational cost and the service quality. As the headway decreases, the passenger in-vehicle time and waiting time were improved while the operational cost was increased. Therefore, the tradeoff between the operational cost and the service quality is mainly affected through the decision on headway. The tradeoff between them was decided based on the passenger time value and passenger waiting time ratio. As the schedule time increased, the passenger waiting time and on time performance were improved while the operational cost was increased given a headway. Therefore, the tradeoff between the operational cost and the service quality should also be considered in setting the schedule time.

There was also a tradeoff between passenger in-vehicle time and waiting time. Given a headway, the in-vehicle time increases as the schedule time is increased while the waiting time decreases. The decision on whether an increase in the schedule time improves the overall service quality or not was affected by the ratio of the value of in-vehicle time to waiting time.

From this case study, revised schedule parameters for route 77 were recommended. Under the current scheduled headway, the recommended schedule parameters could reduce the operational cost by $65 with improving the waiting time by 13 seconds and on time arrival probability by 30%. It showed that applying the proposed scheduling process and the schedule-based holding could save operational cost by reducing unnecessary recovery time while improving overall service quality. With the assumption that the value of passenger in-vehicle time is 10 cents per minute and the ratio of in-vehicle time to waiting time is 1.5, the improved service quality was almost the same as the increased operational cost by providing more frequent service.

By applying the proposed scheduling process, we could explore different combinations of the schedule parameters and estimate the operational cost and service quality for each case. Also, the estimations of the operational cost and the service quality with different schedule parameters enabled the transit agency to consider the tradeoffs between the operational cost and the service quality in the scheduling process.

5.2. Further Research

This research developed and explored the relationships between schedule parameters, operational cost and service quality involved in the scheduling process and proposed a schedule parameter setting process including the step to assess different combinations of schedule parameters and estimate the operational cost and service quality of them with considering the relationships developed before. During the course of study, several areas for further development were identified:

- **Dependent Runs**

In this research, it has been assumed that successive runs are completely independent of each other. In reality, a run will depend on the previous runs. Considering the relationship with the previous run, the departure time at the starting terminal will not always be on time since it is a function of the arrival time of the previous run at the terminal. Therefore, more research is needed to develop a model to estimate the trip time distribution recognizing its dependence on the previous run. It will help to better understand the impact of headway variability on the overall operations.

- **Operational Planning at a network level**

This research developed the relationships involved in setting schedule parameters at a route level. Therefore, the factors affecting operations planning at a network level such as interlining and connectivity, are not considered. Also, the budget constraint existing at the system level is not considered. The budget is assigned to a route based on the marginal benefits gained from the route compared to other routes. Therefore, the schedule parameters of a route cannot be decided by only the tradeoffs between schedule parameters, operational cost and service quality of that route. The tradeoffs of other routes also affect the decision on the schedule of the route. Therefore, the relationships involved in setting schedule parameters should be extended to the network level by incorporating those factors not considered at a route level. Also, developing a better process for the operational planning at a route level will be valuable.

- **Operational Control Strategies and Schedule Parameters**

In this research, a simple operational control strategy, schedule-based holding at time points, was considered. The operational control strategies directly change the mean and variability of trip time, which are critical in setting the scheduled trip time and recovery time. Therefore, research which investigates the impact on the service quality and the schedule parameters setting of different operational control strategies should be valuable. It will help illuminate the relationships between schedule parameters, operations control strategies and operational performance.

- **Integer Number of Buses**

In the proposed scheduling process, the increases in the operational cost were modeled through a simple traditional cost model as a function of changes in vehicle hours and vehicle miles. However, in reality, adding one more bus to a route significantly increases the operational cost and the number of buses assigned to a route is also likely to be constrained. Therefore, it is important to develop a scheduling process recognizing the impact of the number of buses required. It will be helpful to develop a cost model incorporating the cost for adding more buses for estimating operational costs more accurately.

- **Tradeoffs between Operational Cost and Service Quality for the Entire Time Period**

The case study in this research has estimated the operational cost and service quality during the AM peak, and thus, it just showed the tradeoffs between them during a single time period. In a real scheduling context the full operational cost depends on multiple time periods and the time period transitions. The late trip cost also needs to be calculated per day based on the total work time distribution over the day. The tradeoff between this operational cost and service quality for the entire day will help the transit agency find better combinations of schedule parameters.

- **Passenger Time Value and Waiting Time Ratio**

As mentioned earlier, the scheduling process can show the tradeoff between the operational cost and the service quality or the tradeoff between the passenger in-vehicle time and the passenger waiting time. However, the real decisions on the schedule parameters should depends on the true passenger time value and the ratio of the in-vehicle time value to the waiting time value. Therefore, it would be beneficial to have further research on these values.

Reference

Abkowitz, M., Tozzi, J., (1987). Research Contributions to Managing Transit Service Reliability. *Journal of Advanced Transportation,* Vol. 21, pp. 47-65.

Abkowitz, M., Slavin, H., Waksman, R., Englisher, L., Wilson, N., (1978). *Transit Service Reliability.* MA: U.S. Department of Transportation, Transportation Systems Center.

Andersson, P., Scalia-Tomba, (1981). A Mathematical Model of an Urban Bus Route. *Transportation Research B,* 15B, 4, pp. 249-266.

Benn, H. P., (1995). Bus Route Evaluation Standards. TCRP Synthesis of Transit Practice 10, Transportation Research Board, Washington, D.C.

Cain, D., Pekilis, B., (1993). AVLC Technology Today: A Developmental History of Automatic Vehicle Location and Control Systems for the Transit Environment. *IEEE-IEE Vehicle Navigation & Information System Conference*, pp. 581-585.

Casey, R. F., Labell, L. N., LoVecchio, J. A., Ow, R. S., Royal, J. W., Schwenk, J. C., Moniz, L., Carpenter. E. S., Schweiger, C. L., & Marks, B., (1998). *Advanced Public Transportation System: The State of the Art.* MA: Volpe National Transportation Systems Center.

Cima, B., Corby, M., Gulick, R., Vahidi, H., (2001). Transit Signal Priority: A Comparison of Recent and Future Implementations. Paper presented at the 70th Annual Meeting of Institute of Transportation Engineers.

Dessouky, M., Hall, R., Nowroozi, A., Mourikas, K., (1999). Bus Dispatching at Timed Transfer Transit Stations using Bus Tracking Technology. *Transportation Research Part C,* Vol 7, pp. 187-208.

Ding, Y., Chein, S., (2001). Improving Transit Service Quality and Headway Regularity with Real-time Control. Paper presented at the 2001 Annual Meeting of the Transportation Research Board, Washington, D.C.

Furth, P. G., (1980). Setting Frequencies on Bus Route. *MS Thesis: Department of Civil Engineering, Massachusetts Institute of Technology.*

Furth, P. G., (1981). Designing Bus Routes in Urban Corridor. *Ph.D Thesis: Department of Civil Engineering, Massachusetts Institute of Technology.*

Furth, P. G., (2000). Data Analysis for Bus Planning and Monitoring. TCRP Synthesis of Transit Practice 34, Transportation Research Board, Washington, D.C.

Janos, M., (2001), Bus Signal Priority and Operational Control Strategies For the Old San Juan Corridor. *MS Thesis: Department of Civil Engineering, Northeastern University.*

Koutsopoulous, H. N., (1983). Temporal and Spatial Allocation of Buses on a Transit Network with Time Varying Characteristics. *MS Thesis: Department of Civil Engineering, Massachusetts Institute of Technology.*

Liu, G., (1995), Time points and Schedule Design for a Fixed Transit Route Adopting a Holding Control Strategy. *Ph.D Thesis: Department of Civil Engineering, The University of Calgary.*

Muller, T., Furth, P., (2000). Integrating Bus Service Planning with Analysis, Operational Control, and Performance Monitoring. *Revolutionary Thinking, Real Results: ITS 2000: Conference proceedings*, p. 20.

Muller, T., Furth, P., (2001). Trip Time Analyzers: Key to Transit Service Quality. Paper presented at the 2001 Annual Meeting of the Transportation Research Board, Washington, D.C.

Okunieff, P. E., (1997). AVL systems for Bus Transit. TCRP Synthesis of Transit Practice 24, Transportation Research Board, Washington, D.C.

Pine, R., Niemeyer, J., Chisholm, R. (1998). Transit Scheduling: Basic and Advanced Manuals. TCRP Report 30, Transportation Research Board, Washington, D.C.

Starthman, J., Dueker, K., Kimpel, T., Gerhart, R., Turner, K., Taylor, P., Callas, S., Griffin, D., (1999). Automated Bus Dispatching, Operations, Control, and Service Reliability: The Initial Tri-Met Experience. Paper presented at the 1999 Annual Meeting of the Transportation Research Board, Washington, D.C.

Starthman, J., Dueker, K., Kimpel, T., Gerhart, R., Turner, K., Taylor, P., Callas, S., Griffin, D., (2001). Bus Transit Operations Control: Review and an Experiment Involving Tri-Met's Automated Bus Dispatching System. Paper presented at the 2001 Annual Meeting of the Transportation Research Board, Washington, D.C.

Song, W., (1998), Real Time Dispatching Control in Transit Systems. *MS Thesis: Department of Civil Engineering, Massachusetts Institute of Technology.*

Turnquist, M. A., Bowman, L. A., (1980), The Effects of Network Structure on Reliability of Transit Service. *Transportation Research A,* 21A, 2, pp. 93-100.

Wirasinghe, S. C., Liu, G., (1995), Optimal Schedule Design for a Transit Route with One Intermediate Time Point. *Transportation Planning and Technology,* Vol. 19, pp. 121-145.

Wirasinghe, S. C., Liu, G., (2001), A Simulation Model of Reliable Schedule Design for a Fixed Transit Route. *Journal of Advanced Transportation,* Vol. 35, No. 2, pp. 145-174.

Wong, C., (2000), Improving the Network Performance of Urban Transit Systems. *MS Thesis: Department of Civil Engineering, Massachusetts Institute of Technology.*