Improving High-Frequency Bus Service Reliability through Better Scheduling

by

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Abstract

Developing a schedule for high-frequency bus routes involves balancing the costs to the passengers in terms of passenger waiting time and in-vehicle time and the cost to the transit agency. Passengers are interested in short travel times and in short and reliable waiting times. In order to assess the trade-off between trip speed and reliability, transit planners need to follow a clear scheduling process; i.e., a series of steps the scheduler follows to create a schedule.

This thesis develops a scheduling process based on a model which explicitly projects and evaluates the tradeoffs between overall travel time and reliability. The model uses Automatic Vehicle Location and Automatic Passenger Count data and is based on two critical hypotheses: (i) consecutive bus vehicle trips are independent and (ii) consecutive segment running times for a particular bus trips are independent. These two hypotheses will not be true in all cases but were shown to be true on the two CTA bus routes analyzed, 95E and 85. By simulating the running time distributions and headway variability of any proposed schedule, the model estimates the cost of the schedule for waiting passengers, onboard passengers and the transit agency. The scheduling process involves finding the time point schedule which minimizes the total cost with the help of the model.

The scheduling process is applied to two CTA bus routes; Route 95E and 85. For each route, the schedule which minimizes the total passenger cost was determined. The operating cost of the proposed schedule on each route is the same as for the current schedule because the same number of buses is used. The schedules obtained with the generalized cost minimization approach showed improved reliability and overall passenger service quality compared to the current schedule in both routes as well as compared to traditional approaches.

A sensitivity analysis showed that in most cases the generalized cost minimization schedule can significantly improve reliability and overall passenger service quality over traditional approaches.

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Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

This thesis investigates the potential for improved scheduling to have a beneficial impact on the reliability of high-frequency bus routes. A model is developed which evaluates a proposed schedule in terms of the impact on service reliability, passenger service quality and operating cost. The thesis applies the scheduling process to two Chicago Transit Authority (CTA) bus routes using data from Automatic Data Collection (ADC) systems and assesses the benefits to passengers and the transit agency. The benefit to the passengers will be savings in the total travel time and the benefit to the transit agency will be an improvement in the efficiency of bus operation. The results of the thesis can be applied to improve the scheduling of any high-frequency CTA bus route, as well as other transit agencies' high-frequency bus routes, although the model rests on several hypotheses and assumptions which may not be true for all high-frequency transit routes.

1.1. Motivation

Bus service reliability is critical to passengers who are counting on their bus service to be on time. Reliability can encourage potential customers to use transit and current customers to continue to use transit. Depending on the type of bus route, low-frequency or high-frequency, passengers perceive differently reliability. On low-frequency bus routes (i.e., routes whose headway is more than ten-fifteen minutes), passengers usually arrive at stops based on a published schedule [9]. Consequently, a reliable service for the passengers on a low-frequency bus route is a service where buses arrive at stops on time (i.e., where the difference between the actual arrival time and the scheduled arrival time is very small). On low-frequency bus routes, consecutive trips are usually independent because of the long headways between runs and unreliability rarely propagates to following buses.

Conversely, on high-frequency bus routes, with headways of less than ten-fifteen minutes passengers usually arrive at stops randomly. On these bus routes, a reliable service is one where their expected waiting time is small or in the ideal case where the headway is constant and equal to the scheduled headway. On high-frequency bus routes, unreliability propagates easily to following buses because of the short headways and the interaction between buses. The consequences of unreliability for passengers include crowding, longer waiting time because of large gaps in service, missed appointments, higher travel time uncertainty and bus bunching. Bus bunching is a phenomenon which occurs on high-frequency bus routes when a bus falls behind schedule and the following one catches up. The late bus has to pick up more and more passengers due to its long headway following the preceding bus and consequently goes slower as the trip progresses. Meanwhile, the following bus will tend to pick up less and less passengers due to its short headway and will move faster as the trip progresses. The two buses eventually form a pair. Bus bunching frustrates passengers who often have been waiting for a long time until they see two (or more) buses arriving together. Bus bunching also makes transit agency's operation less efficient. Furthermore, some buses may be so late at terminals that reliability problems propagate to following trips. An unreliable service on a high-frequency bus route also affects the transit agency in terms of the number of vehicles required, overtime and increased operating costs for standby drivers, and in lost revenue due to reduced ridership [2]. This thesis will focus on improving bus service reliability on high-frequency bus routes.

Cham [9] has identified various causes of unreliability: (i) schedule deviations at terminals, (ii) passenger load variability, (iii) running time variability, (iv) environmental factors and (v) operator behavior. Abkowitz's transit reliability study [1] considers two categories of strategies to improve service reliability: planning strategies and real-time strategies. Planning[1] (i.e. preventive) strategies are aimed at reducing the likelihood of deviations occurring. Such strategies respond to problems of a persistent and predictable nature. Real-time (i.e. corrective) strategies are directed at restoring service to normal when deviations have occurred. Preventive strategies are a logical focus to improve reliability problems caused by running time variability because it is easier to avoid bus bunching than to cure it.

Transit planners acknowledge that running time variability is an important cause of unreliability since it affects the overall on-time performance and the headway variability. The running time is variable due to traffic conditions, operator behavior and other externalities, as explained by Cham [9]. The most common approach, among preventive strategies, is to seek to adjust schedules in order to reduce running time variability and, consequently, reduce headway variability. A schedule indicates to the operators the scheduled departure time from each time point along the route. A time point is a bus stop at which the scheduled departure time is given to the operators and (sometimes) to passengers. Operators are instructed not to leave a time point

[1] The definitions of the preventive and corrective strategies are taken from Cham [9].

early when a schedule-based holding strategy is enforced. The schedule-based holding strategy[2] is a self-monitoring measure in which the driver must hold his or her bus at a time point until its scheduled departure time if arriving early, and departs from the time point immediately upon completion of passenger processing if arriving late. The holding control strategy applies to each time point excluding the terminals where the operator may rest after all passengers get off the bus but has to leave if he arrives after the scheduled departure time.

Developing a schedule is quite complex since passengers are interested in a reliable service and in short in-vehicle travel time while the transit agency is also interested in minimizing operating costs. An intuitive approach to improve bus service reliability would be to allocate more scheduled running time between time points and more layover time at terminals. However, allocating more scheduled running time between time points increases passenger in-vehicle travel time when schedule-based holding is enforced. Similarly, allocating more layover time at terminals increases operating costs if the transit agency wants to maintain the scheduled headway. Consequently, transit planners have to face trade-offs between service reliability, passenger service quality and operating cost when designing a schedule.

However reliability improvement also depends on operator behavior, as stated previously, and on adequate supervision to control headway and schedule adherence, especially at terminals. Indeed, it is very difficult to maintain reliability if operators leave the terminals erratically since it will create headway variations and eventually bus bunching. Also, operators tend to drive differently from one another depending on their years of experience and characteristics: some operators tend to drive more aggressively while others tend to drive more cautiously. These differences in operation result in running time variability and consequently in headway variability triggering unreliability.

Fortunately, with the development of technologies such as Automatic Vehicle Location (AVL) and Automatic Passenger Counters (APC), larger amounts of data are now becoming available to evaluate and adjust schedules. At the same time, Automatic Data Collection (ADC) systems provide more accurate data and reduce the need for expensive manual data collection to support a more robust schedule development process.

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[2] The definition of the schedule-based holding strategy has been taken from Liu [18]

1.2. Objectives

The objectives of this thesis are fourfold:

1. To better understand the impact of scheduling on high-frequency bus route performance
2. To develop a model to assess different scheduling approaches
3. To develop a scheduling process[3] for improving service reliability on any high-frequency bus route and make recommendations under which the scheduling process might be implemented
4. To apply the scheduling process to two high-frequency bus routes in the Chicago Transit Authority (CTA) network and examine its effectiveness

A thorough literature reviews shows that little research has been undertaken on the development of a scheduling process for high-frequency bus routes. However, related issues, such as reliability related to low-frequency bus routes and bus travel time have been widely researched and have been very helpful in the development of the approach used in this thesis. The following two sections review previous work on which the proposed approach has been based and describe current practice in setting running and recovery times.

1.3. Literature Review

This section outlines previous research by other authors in the field which acts as a starting point for this thesis. Section 1.3.1 reviews the comprehensive study of transit service reliability by Abkowitz and Tozzi and section 1.3.2 presents the major causes of unreliability. Sections 1.3.3 describes TriTAPT, an existing tool which can help schedulers in developing running times and evaluating passenger service quality while section 1.3.4 reviews previous work focused on the improvement of reliability on low-frequency bus routes. Finally, section 1.3.5 describes work on the development of more effective operating plans for bus services.

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[3] A scheduling process is comprised of a series of steps the scheduler implements in order to establish an improved schedule

1.3.1. Managing transit service reliability

Abkowitz and Tozzi [5] reviewed contributions which have been made to understanding improving transit service reliability. Strategies to improve reliability are commonly divided into two categories: planning (i.e. preventive) and real-time (i.e. corrective). Planning strategies are aimed at reducing the likelihood of deviations from occurring by responding to problems of a persistent and predictable nature. Real-time strategies are directed at restoring service to normal when deviations have occurred.

Abkowitz and Tozzi first reviewed models of running time and running time variation. Abkowitz and Engelstein [2] used regression analysis to estimate an empirical model of run time, based on bus operation data from Cincinnati. The running time model which was developed depends on a number of variables such as the number of signalized intersections and percentage of on-street parking between stops. The same model was validated using ride check data from four bus routes in Boston. A running time variation model was also developed by Abkowitz and Engelstein [12]. However, this was subsequently shown to underpredict the actual running time deviation [5]. In fact, it emerged that the Bus Transit Monitoring Manual [20] default values for run time variation were a better predictor, although this too underpredicted observed results [5].

Abkowitz and Tozzi then reviewed research on headway variation and passenger waiting time. Abkowitz et al. [4] developed an empirical headway variation model which showed that headway variation does not increase linearly along a route. Rather the headway variation increases sharply at low values of running time variation and then tapers off. This is because once busses become bunched the system effectively reaches a steady, if unreliable, state. Passengers mostly perceive reliability in terms of the time they spend waiting, if the difference between the bus arrival time and the passenger arrival time. The expected waiting time, E(W), of a passenger who arrives at stop at a random time, which is typical on high-frequency bus routes, under the assumption that the vehicle capacity is not constraining, has been derived by Welding [23], Holroyd and Scraggs [14], Osuna and Newell [21]:

$$E(W) = E(H)/2 + V(H) / 2E(H) \qquad (1\text{-}1)$$

where:

$E(W)$ = *expected wait time for a passenger at a stop*

$E(H)$ = *expected headway*

$V(H)$ = *headway variance*

Lastly, Abkowitz and Tozzi reviewed research on real-time control strategies. The objective of Osuna and Newell [21] was to find the optimal holding time on a route with one service point and one or two vehicles in order to minimize the average waiting time for passengers. Holding is a real-time control strategy which consists in delaying a bus at a control point. The decision to hold is usually taken by the bus supervisor at the control point. Osuna and Newell found that control should only be applied after the service deterioration has already occurred, not in anticipation of a potential problem. However, their model was mostly based on intuition. Barnett [6] developed a model of a route with multiple stops where one stop was designated a control point. His objective was to find the dispatching headway from the control point to optimize the reduction in wait time versus the delay to passengers on-board at the control stop. Bursaux [8] further developed Barnett's research by designing an analytical approach to determine the optimal location of the control point. He tried to apply his methodology to an MBTA bus route but this was not successful because of the mathematical complexity. Bly and Jackson [7] and later Koffman [17] used simulation models to evaluate control strategies. They all found that holding produced very small improvements in wait time at the expense of longer passenger travel time.

1.3.2. Analysis of bus service reliability

Cham [9] reviewed the key elements of service reliability, focussing on the measures of reliability, the causes of unreliability and the application of strategies to improve service reliability. Her research identified five major causes of unreliability: deviations at terminals, passenger load variability, running time variability, environmental factors and operator behavior. Each cause of service unreliability, as well as their impact on bus service reliability and the inter-relationships between the causes were reviewed. Her research also presents the potential preventive and corrective strategies and the best strategy for each cause of service unreliability. Cham proposed a practical framework for a transit agency to assess their bus service reliability and applied it to the MBTA Silver Line, which is a bus rapid transit route.

1.3.3. TriTAPT

Furth et al. [11] reviewed the different types of AVL and APC data collection systems and suggested design principles for AVL-APC data systems. AVL-APC systems should store data on board in order to be free of the capacity constraints associated with transmitting data over the air. The data should be at the stop level for geographic precision and to provide better information for passengers. They were critical of using a simple "polling" system alone, which indicates the bus position at fixed time intervals. Busses should be equipped with devices such as door sensors, odometers and a radio control head in order to identify holding as well as to deal with multiple apparent stops and starts at bus stops and at the terminal. Transit planners are encouraged to integrate Automatic Vehicle Location data with Automatic Fare Collection data to measure accurately ridership patterns.

Furth et al. also presented tools to analyze the data collected, relating it to waiting time, crowding and running time. The first tool, which is part of the software package, TriTAPT [19], is a tool based on historical data. Data is gathered using an on-board AVL system and fed into TriTAPT, a system which records both time and location data during each transit vehicle trip for subsequent (offline) reconstruction of bus trip trajectories. Such analysis provides operational measures like trip time, schedule adherence and headway deviations. In contrast to automated data collection systems, trip time analyzers provide the user, not only with automated data collection but also offline analysis capabilities.

TriTAPT can help schedulers, in particular, in improving the schedule of a bus route. It produces a statistical summary of end-to-end running time for each trip based on many days of observation. Schedulers can see the mean running time and variability. TriTAPT can also provide the scheduler with time periods and scheduled running times for each time period after the user specifies a percentile band (for example, the user selects scheduled times that lie between the 75th and 95th percentile observed running time). Alternatively, the user might propose time periods and scheduled running times and see how these running times would perform. Running time analyses are invariably based on the running time data record of net trip time[4].

For schedule adherence, running time should be scheduled at the segment level in order to prevent large schedule deviations. The approach adopted to find the passing moments (i.e., scheduled times at time points) is to set the scheduled running times (from each time point to the end of the line) at a level where 85 percent of the trips would have sufficient time to complete the trip as shown in Figure 1-1. By building the cumulative density function from each time point to the end of the route, one can determine the recommended scheduled running time. Scheduled segment running times, which are the scheduled running time between two consecutive time

[4] The net trip time is the running time minus the holding time at time points.

points, are then found by repeated subtraction. This method provides an incentive to operators to hold when they are ahead of schedule since the developed schedule always maintains a probability of 0.85 that the trip is completed on time. Thus schedule adherence is improved. Unfortunately, this method usually sets significantly longer scheduled running times which disadvantage through passengers who are held longer at time points. TriTAPT is currently in use in Eindhoven, a city of 210,000 inhabitants in the Netherlands.

The second tool evaluates waiting time and crowding using a framework composed of three measures of waiting time. The three measures are budgeted waiting time, potential waiting time and equivalent waiting time. The budgeted waiting time and potential waiting time reflect the amount of time passengers budget for waiting on high-frequency bus routes and low-frequency bus routes respectively. The equivalent waiting time is the total economic value of waiting time for the passengers. These measures are sensitive to service reliability and are based on extreme values of the headway and schedule deviation distribution, which most affect customer satisfaction [11]. This tool presents a whole new framework to measure the effects of service reliability on passenger waiting time.

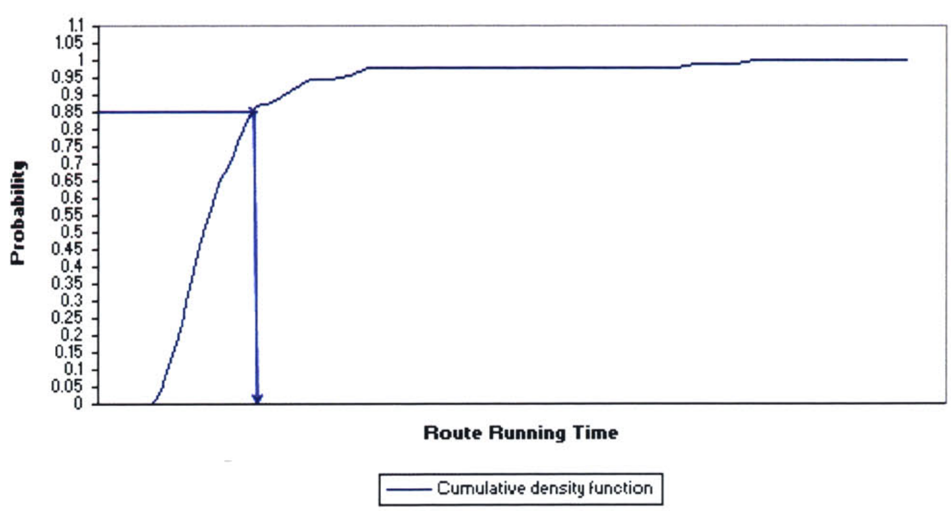

Figure 1-1 Route running time cumulative distribution

A new measure is also developed to evaluate crowding from the Automatic Passenger Count data. It is a measure of service quality which shows the number of passengers who sit and who stand at the maximum load point, the percentage of people standing and the percentage of people sitting next to an empty seat. This measure can help transit agency better assess their service quality.

Furth et al. also provide methods to process and use Automatic Passenger Count (APC) data. These data often show under or over counting, making it difficult for the transit planners to use these raw data to analyze bus service. By comparing the APC data with manual checking, they found that the accuracy of the load is often worse than the accuracy of the number of passengers boardings or alightings. They suggest parsing (i.e. balancing the ons and offs) the data at points of known load such as layover points where the load is known to be zero. Correctly parsing the data will allow more accurate load estimation at each stop or timepoint.

1.3.4. Improving bus service reliability on low-frequency bus routes

Wirasinghe and Liu [24] developed a cost-based model to design a schedule for a simple two-link low-frequency bus route assuming a schedule-based holding strategy at time points. The schedule was determined by minimizing the mean total cost associated with the schedule which is the sum of: (i) the passenger waiting time cost, (ii) the delay cost to through passengers, (iii) the delay/early penalty and (iv) the operating cost. They demonstrated that the optimal schedule is sensitive to the demand pattern along the route and that there is a need to set time points only when the number of boarding passengers is much greater than the number of through passengers. Consequently, they proposed that the amount of slack time at those time points should increase with the ratio of boarding passengers to through passengers. Their research was a significant advance in the area of optimal schedule development. However the work assumed: (i) coordination of passenger arrivals at stops with arrival of the bus and (ii) independence of successive bus runs. These assumptions are generally true on low-frequency bus routes but much less so on high-frequency bus routes and therefore their model cannot be applied directly to the problem defined in this thesis. Furthermore, they defined the waiting time cost as a function of the scheduled departure time at stops since service quality is controlled by schedule adherence on low-frequency bus routes. However waiting time cost on high-frequency bus routes should be defined as a function of the actual headway since service quality on those types of routes is controlled by headway adherence.

Furth and Muller [12] explored the tradeoff between reliability, riding time and operating cost impacts on long headway transit routes using a simple route operation model. To examine the tradeoff between speed and reliability, they defined a set of three components of user cost expressed as economic values in dollars: (i) excess waiting time, (ii) potential travel time and (iii) mean riding time. Passengers on long headway routes want to limit the probability that they miss their targeted departure, and therefore can be expected to arrive before the bus's 2-percentile departure time. Thus, the excess waiting time is the difference between the passenger's arrival time and the 2^{nd}-percentile departure time. It is a measure of the uncertainty in access time. The potential travel time is the total amount of time passengers budget for waiting at stops and for travel in order not to arrive at their destinations late. The potential travel time is a reliability-related measure. Another tradeoff explored was between cost to the transit agency and cost to the passengers. The study found that adding slack time at time points does not increase operating costs because the slack added en route allows for a reduction in the layover time at a terminal. They further demonstrated that route running times should be set at roughly the mean plus one standard deviation of uncontrolled running time and cycle time at roughly the mean plus two to three standard deviations of uncontrolled route running time on long headway transit routes, confirming the common practice in the Netherlands.

1.3.5. Developing more effective operating plans for bus services

Hong [15] developed relationships between schedule parameters, operational cost and service quality involved in the scheduling process. She showed the influence of time points and schedule time on trip time. She showed how to divide vehicle trip time into vehicle movement time and dwell time and how the trip time distribution changes with the schedule parameters. She also derived a mathematical expression to find the distribution of arrival time at a terminal on a two-segment route with one time point assuming a schedule-based holding strategy as well as demonstrating how to extend the model to a route having multiple time points. However, her model assumes independence among consecutive runs and allowed a non-integer numbers of buses.

1.4. Current Practice

Before the recent development of Automatic Data Collection systems, schedulers had to determine running times based on limited manually collected data, in response to complaints, and using considerable professional judgment. Even today, transit agencies without Automatic Data Collection (ADC) systems must develop timetables this way. However, transit agencies with new ADC systems often continue to use these methods because of a lack of research in the area. These methods help only in developing a "workable" schedule which is based on the little data available.

"Rules of thumb" are often applied by schedulers. These rules of thumb often vary from one transit agency to another. However, one common approach [22] is to:

1. Set running times at a level where at least 65% of trips would have sufficient time to complete a route or a segment.
2. Set layovers (or recovery time) at a level that would allow at least 90% to 95% of operators to depart their next trip on time.

Other "rules of thumb" [16] are to:

1. Set running time between time points equal to the mean observed running time
2. a) Set layover time in order to have the scheduled cycle time equal to the 95^{th}-percentile of the route running time. (The scheduled cycle time which is equal to the 95^{th} percentile of the route running time is determined using the cumulative density function, as explained in section 1.3.3).

   b) Or set the layovers at a fixed percentage, typically 10%, 15% or 18% of the scheduled running time.

However, extensive data is required to apply such rules. Indeed the only way to estimate the 95^{th} percentile with confidence is to have large amounts of data in order to build a running time distribution. It is important to estimate the 95^{th} percentile with confidence because transit managers want to avoid late departures from the terminal.

1.5. Research Approach

The primary goal of this thesis is to investigate the potential for improved scheduling to have a beneficial impact on reliability of high-frequency bus routes. After exploring the influence of time points on the departure time distribution from each time point if a schedule-based holding strategy is enforced, a cost-based model will be used to help evaluate a proposed route schedule. The schedule is determined by minimizing the mean total passenger cost associated with the schedule which is the sum of passenger waiting time cost and passenger in-vehicle travel time cost. By translating reliability and passenger service quality to economic values, it is easier to assess the trade-offs between speed and reliability.

The use of a cost-based model will be demonstrated on two case studies using Chicago Transit Authority bus routes. The AVL-APC data of two Chicago Transit Authority bus routes will be used in order to compute the outcomes in terms of service reliability, passenger service quality and operating cost of the schedule obtained by minimizing on each segment of the route the sum of passenger waiting time cost and passenger in-vehicle travel time cost. The outcomes of the schedules obtained with the generalized cost minimization approach will be compared with the outcomes of schedules designed with traditional approaches, as described in section 1.4, for the two Chicago Transit Authority (CTA) bus routes. The benefits and potential drawbacks of each approach will be considered in the final recommendations.

The scope of this research is to investigate the efficiency of a cost-based scheduling process to improve bus service reliability for a high-frequency bus route which incorporates the schedule-based holding strategy. This work does not consider more complex scheduling issues such as interlining, transfers between routes, and deadhead reduction. The thesis does not help identify the optimal headways and optimal time points but simply attempts to determine the optimal scheduled running times on each segment (i.e. between two consecutive time points) of a given route which will improve bus service reliability given today's scheduled headways and time points.

1.6. Thesis Organization

Chapter 2 discusses the scheduling process. In Chapters 3 and 5 respectively, the scheduling process is applied to Route 95E and Route 85 of the Chicago Transit Authority. Chapter 4 performs a sensitivity analysis. Chapter 6 summarizes and discusses the findings of the analysis and makes recommendations for future research.

Chapter 2. Scheduling Process

This chapter presents a proposed scheduling process which can help transit agencies design bus route running times which improve bus service reliability. Section 2.1 presents the general modeling approach. Section 2.2 presents the basis for the model including the underlying hypotheses and assumptions, as well as the way to establish the recovery time. The analysis process to be applied in the following application chapters is then presented in section 2.3.

2.1. General Model Structure

The goal of this thesis is to improve bus service reliability on high-frequency bus routes by establishing better schedules. The schedule indicates to the operator the scheduled running time on each segment of a route. The difficulty of the problem lies in the fact that we cannot solve this problem experimentally, i.e. by trying various schedules in the field to see what the consequences are on bus service reliability. Consequently, we have to model how a new schedule is going to impact bus service reliability. This section explains the general model structure.

As explained in chapter 1, bus service reliability is a function of headway adherence on high-frequency bus routes since passengers generally arrive randomly at stops on such routes. Passengers will experience good reliability on high-frequency bus routes if the actual headways are constant and equal to the scheduled headway. Consequently, we have to model the impact of a new schedule on the headway variability to verify if the schedule would improve bus service reliability. Assuming that operators follow a schedule-based holding strategy, Hong [15] developed a theoretical model to study the influence of scheduled running time on the distribution of the actual arrival time at the terminal for a route with one time point. However, her model assumed that consecutive runs were independent. Based on her work and also assuming operators follow a schedule-based holding strategy, we have developed a model which gives the actual arrival and departure times at each time point for each vehicle on a route with n time points, given a proposed time point schedule and the current scheduled headway. From the actual departure times from each time point obtained from the model, the actual headway and the headway variability can be computed. Thus, the service reliability for the passengers can be estimated.

From the running times developed by the user and the number of buses to be operated on the route, the model derives the total scheduled layover time for the route. The amount of time allocated at each terminal will determine the headway variability and consequently the reliability experienced by passengers.

Allocating more scheduled running time on each segment of the route and more layover time at each end of the route will result in improved service reliability at an increased operating cost. Indeed, it will reduce the headway variability thanks to the schedule-based holding strategy. Thus, early buses will have to wait at each time point until the scheduled departure time. However, there is a limit to the resulting improvement in overall bus service quality. First, holding early buses a few minutes at each time point will lower the overall quality of the bus service since through passengers will be delayed at each time point. (Through passengers are the passengers who do not get off at the time point and consequently experience the holds at the time point). Second, if the transit agency allocates too much scheduled running time on each segment of the route and too much layover times at the terminals, then it will have to increase the number of buses in order to maintain the same scheduled headway. Consequently, the proposed schedule design must balance the improvement in service reliability against the increased cost both for the through passengers and for the transit agency. To evaluate the trade-off between reliability, speed and operating cost, a simple cost model is used to translate the reliability and the passenger service times into economic values. Thus, the costs to waiting passengers, onboard passengers and to the agency can be found for each schedule tested.

In summary, the descriptive model proposed here simulates the scheduled departure time from each time point along a route with a new schedule. It consequently estimates the passenger waiting time cost, the passenger in-vehicle cost and the operating cost of a proposed schedule. By systematically varying the schedule parameters the schedule which minimizes the passenger total cost can be identified. The inputs to the model are: the current AVL and APC data, the schedule segment running times, scheduled headway and the scheduled number of buses. The outputs are the waiting passenger cost, the in-vehicle travel time cost and the operating cost.

The step-by-step process of the model is as follows:

1. The user inputs:

    - the segment running time distributions (from the departure time at the starting time point to the arrival time at the next time point) and segment cumulative density functions based on the AVL data.

    - the scheduled segment running times by choosing on each segment the percentage of trips which can operate within the scheduled segment running time. If, for example the user wants to evaluate a segment scheduled running time which is the 60th percentile of the segment cumulative density function, the scheduled running time on that segment should be 1.5 min, as shown in Figure 2-1.

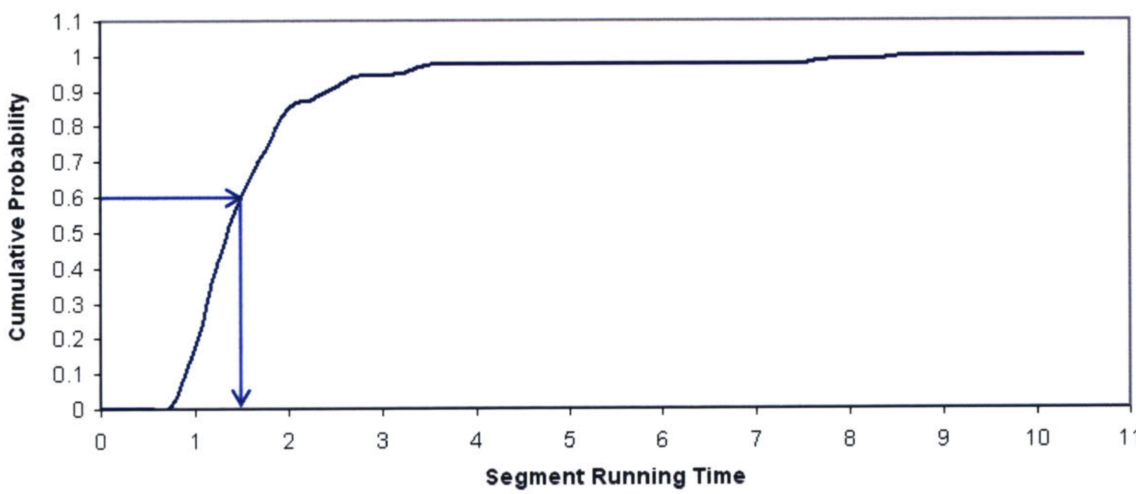

Figure 2-1 Segment Cumulative Density Function

- the average load on each segment of the route

- the passenger arrival rate on each segment

- the number of buses in operation during the hour under consideration

- the scheduled headway during the hour under consideration

- the allocation of the recovery time between the two ends of the route. (The total recovery time is already specified by the number of buses, scheduled headway and scheduled segment running times).

2. The model implements the scheduled running times and scheduled headway chosen by the user from the beginning of the day. It, then, simulates the vehicles'arrival and departure times from each time point on the route throughout the day up to the hour of operation studied, assuming that the same buses are used continuously.

3. For a given trip, the segment running time (from the departure time at the starting time point to the arrival time at the ending time point) is drawn randomly from the segment running time distribution.

4. The model calculates the departure times of each trip from each time point. With a schedule-based holding strategy enforced, the departure time from a time point is equal to the scheduled departure time if the vehicle arrived before the scheduled departure time or equal to the sum of the arrival time and dwell time at the time point if the vehicle arrived after the scheduled departure time.

5. From the arrival and departure times, the model calculates the average and coefficient of variation for arrival and departure headways at each time point.

6. Also, from the departure times, the model calculates the average time vehicles spend on each segment (from the departure time at the starting time point to the departure time at the next time point).

7. From the arrival and departure times at each terminal, the model calculates the average recovery time.

8. The passenger waiting time cost on each segment of the route is calculated by the model during the hour of operation studied. It is a function of the average headway, headway coefficient of variation and the expected number of passengers waiting on the segment weighted by the unit waiting time cost. The total waiting time passenger cost, which is the sum of the waiting time cost on each segment of the route, is calculated.

9. The in-vehicle passenger cost on each segment of the route is calculated. It is a function of the average running time on the segment and average load on the segment (during the

hour of operation studied) weighted by the unit in-vehicle travel time cost. The total in-vehicle travel time passenger cost, which is the sum of the in-vehicle travel time passenger cost on each segment of the route, is also calculated.

10. The total passenger cost is the sum of the total waiting passenger cost and total in-vehicle passenger cost.

11. The scheduled operating cost is calculated. It is a function of the number of buses in operation, and the operating cost per hour.

The user can evaluate the cost of other schedules by changing the schedule parameters in step 1. Thus, the tool can be used to compare and evaluate alternative schedules by minimizing the total passenger cost.

2.2. Basis for Running Time Model

The running time model proposed here is based on two key hypotheses and four additional assumptions:

1. The running time of a specific bus on a segment is independent of its headway with the immediately preceding bus

2. The running time of a specific bus on one segment is independent of its running time on the preceding segment

3. The passenger arrival rate is constant over a time period

4. All passengers can board the first bus

5. The schedule-based holding strategy is enforced

6. The scheduled segment running time does not affect the running time distribution

The first two hypotheses are discussed in detail and tested in sections 2.2.1 and 2.2.2 below using data from two routes of the Chicago Transit Authority (CTA) network. After that the four additional assumptions are discussed more briefly in section 2.2.3.

2.2.1. Relationship between segment running time and headway

On high demand, high frequency bus routes, it is generally expected that if a bus falls a few minutes behind schedule and, more importantly, the gap widens between it and the bus ahead of it, the second bus will have to pick up more passengers and consequently its running times will increase. The relationship between running time and headway can be tested for CTA bus Routes 95E and 85 which will be used as case studies to evaluate the proposed scheduling process. If this hypothesis is not reasonable (i.e. there is a clear relationship between running time and headways), we will have to refine the running time model and the scheduling process. To determine whether this hypothesis is reasonable, a correlation analysis between the segment running times and the headways departing the initial time point is performed. The segment running time is the time from the departure from the segment's starting time point to the arrival at the ending time point.

The correlation analysis relates the running time on the segment and the ratio of the actual headway to the scheduled headway with the preceding bus. The ratio between the actual headway and the scheduled headway (or headway ratio) is used to avoid errors which may be incurred if data for a trip is missing. Indeed if a trip was missing from the data set, the headway would seem greater than it was and the correlation analysis would consequently be erroneous. Using the ratio of the actual headway to the scheduled headway avoids this problem.

a) <u>Route 95E</u>

Tables 2-1 and 2-2 show the results of the correlation analysis for Route 95E Westbound and Eastbound respectively during the afternoon peak between 16:00 and 17:00.

	Correlation Coefficient R between Running Time and Headway Ratio	Determination Coefficient R^2
92 Buf – 92 Com	0.16	2.7%
92 Com – 94 Sto	- 0.10	1.0%
94 Sto – 93 Cot	- 0.08	0.6%
93 Cot – 95 Red	0.03	0.1%

Table 2-1 Running Time – Headway analysis for Route 95E Westbound

	Correlation Coefficient R between Running Time and Headway Ratio	Determination Coefficient R^2
95 Red – 93 Cot	0.09	0.8%
93 Cot – 94 Sto	0.09	0.8%
94 Sto – 92 Com	- 0.02	0.0%
92 Com – 92 Buf	0.4	16.5%

Table 2-2 Running Time – Headway analysis for Route 95E Eastbound

From Tables 2-1 and 2-2, we note that there is no strong correlation on most segments except on the last Eastbound segment. However, it is known that operators behave erratically on the last Eastbound segment and the first Westbound segment of Route 95E. Moreover, there is no real reason to expect strong correlation on 92 Com-92 Buf since there are very few passengers boarding on that segment in this time period: on average only 0.4 boardings per trip. The correlation is sometimes positive, i.e. as the headway increases, the running time increases, and sometimes negative, i.e. as the headway increases, the running time decreases. The correlation between the headway and the running time should be positive when the gap between two buses becomes significant and more passengers are waiting to board which increases the running time. On the other hand, when buses are bunched, the running time of the second bus will not be a function of the headway ratio but will be highly correlated with its leader's running time. The data analysis shows that while the correlation is sometimes positive and sometimes negative, it is always so small that we can neglect the correlation between the running time and the headway. Indeed, the headway never explains more than 1% of the variation in the running times except for the two unusual segments discussed above.

Figures 2-2 and 2-3 show the headway ratio and running times on the segments which have the strongest correlation, 92 Com – 94 Sto, and the weakest correlation, 94 Sto – 92 Com, respectively. (Segment 92 Com-92 Buf is not used because operators behave erratically on that segment). The horizontal (red) line indicates when the actual headway is equal to the scheduled one. The vertical (red) line shows the scheduled running time on the segment.

In both these segments the correlation between the headway and the running time is negative; as the headway increases, the running time tends to decrease. However the lack of correlation between the running time and the headway on 92 Com-94 Sto and 94 Sto-92 Com is evident in both figures with the dots representing the data points widely scattered and not forming any clear relationship.

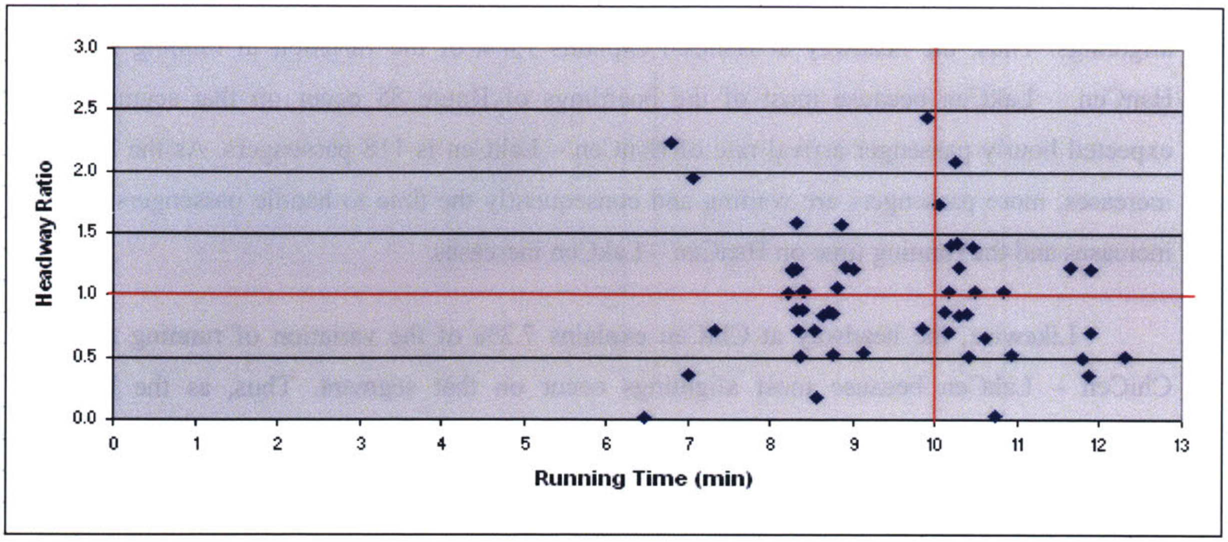

Figure 2-2 Headway Ratio vs. Running time for 92 Com – 94 Sto

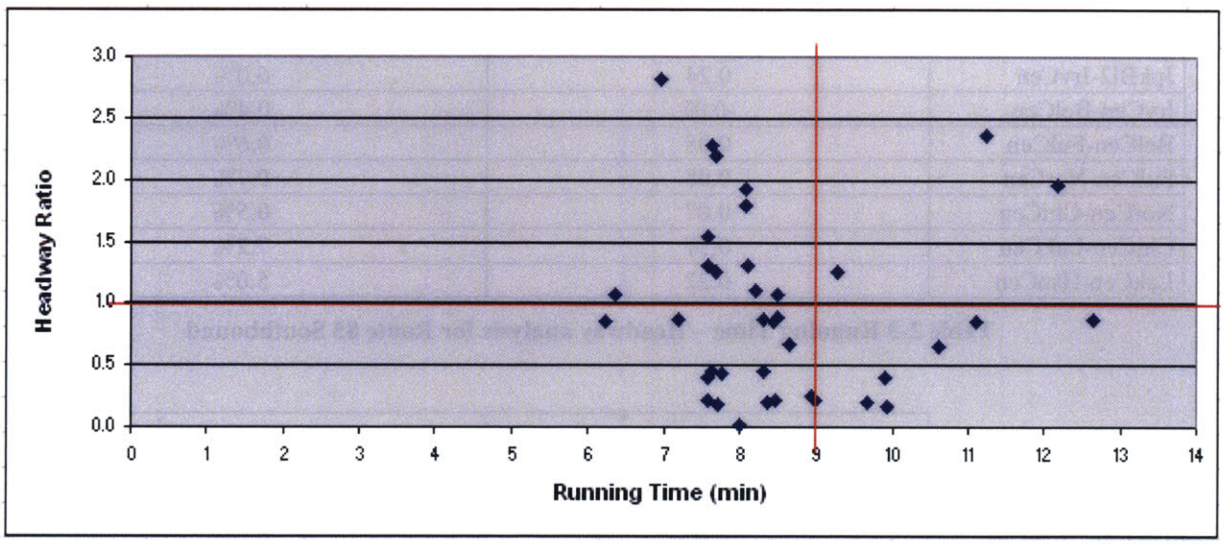

Figure 2-3 Headway Ratio vs. Running time for 94 Sto – 92 Com

b) Route 85

Tables 2-3 and 2-4 show the corresponding correlation analysis for Route 85 Southbound and Northbound respectively during the morning peak between 7:00 and 8:00.

From Tables 2-3 and 2-4, we note that there is no strong correlation between the headway and the running time on most segments. The headway explains at most 7% of the variation in the running time and the correlations are both positive and negative. We note that the running time shows some correlation with the headway on the segments which have more boardings or more alightings. Thus, the headway at HsnCen explains 7.4% of the variation in running times on HsnCen – LakCen because most of the boardings of Route 85 occur on that segment. The expected hourly passenger arrival rate of HsnCen – LakCen is 118 passengers. As the headway increases, more passengers are waiting and consequently the time to handle passengers at stops increases and the running time on HsnCen – LakCen increases.

Likewise, the headway at ChiCen explains 7.2% of the variation of running times on ChiCen – LakCen because most alightings occur on that segment. Thus, as the headway increases, the bus picks up more passengers en route and consequently more passengers will need to alight on this segment. As the number of people who need to alight increases, the dwell time increases and so does the running time.

	Correlation Coefficient R between Running Time and Headway Ratio	Determination Coefficient R^2
Bm Els - JpkBlu	- 0.12	1.6%
JpkBl2-IrvCen	0.24	6.0%
IrvCen-BelCen	-0.07	0.4%
BelCen-FulCen	0.08	0.6%
FulCen-NorCen	0.08	0.7%
NorCen-ChiCen	0.07	0.5%
ChiCen-LakCen	0.27	7.2%
LakCen-HsnCen	0.22	5.0%

Table 2-3 Running Time – Headway analysis for Route 85 Southbound

	Correlation Coefficient R between Running Time and Headway Ratio	Determination Coefficient R^2
HsnCen - LakCen	0.27	7.4%
LakCen - ChiCen	0.00	0.0%
ChiCen - NorCen	0.12	1.5%
NorCen - FulCen	-0.13	1.8%
FulCen - BelCen	-0.19	3.7%
BelCen - IrvCen	-0.23	5.4%
IrvCen - JpkBlu	-0.22	4.8%
JpkBlu - Bm Els	0.10	1.0%

Table 2-4 Running Time – Headway analysis for Route 85 Northbound

Figures 2-4 and 2-5 show the headway versus the running time on the segment with the highest correlation, HsnCen - LakCen, and the lowest correlation, LakCen - ChiCen, respectively.

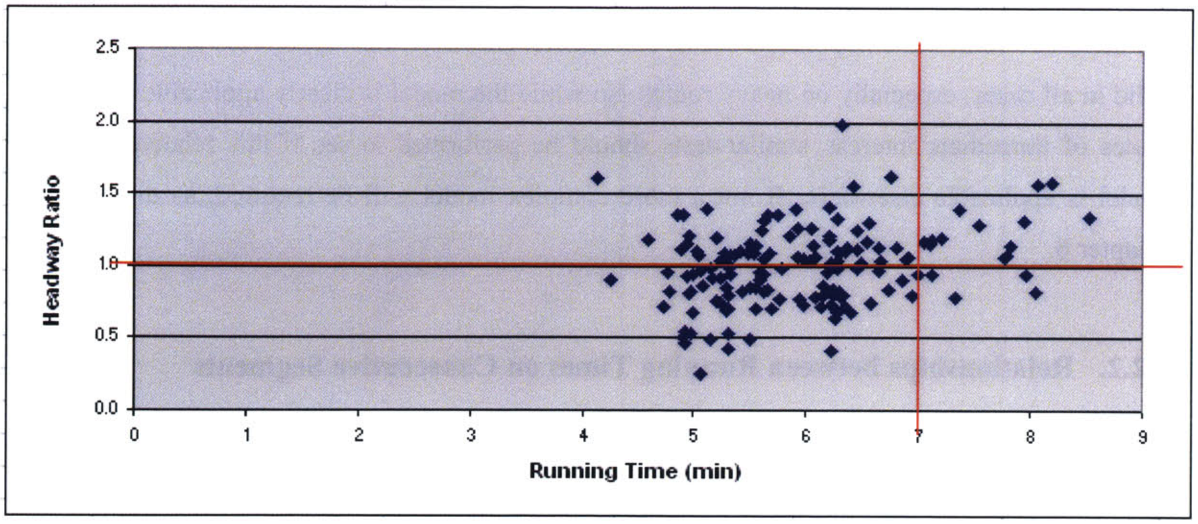

Figure 2-4 Headway Ratio vs. running time for HsnCen – LakCen

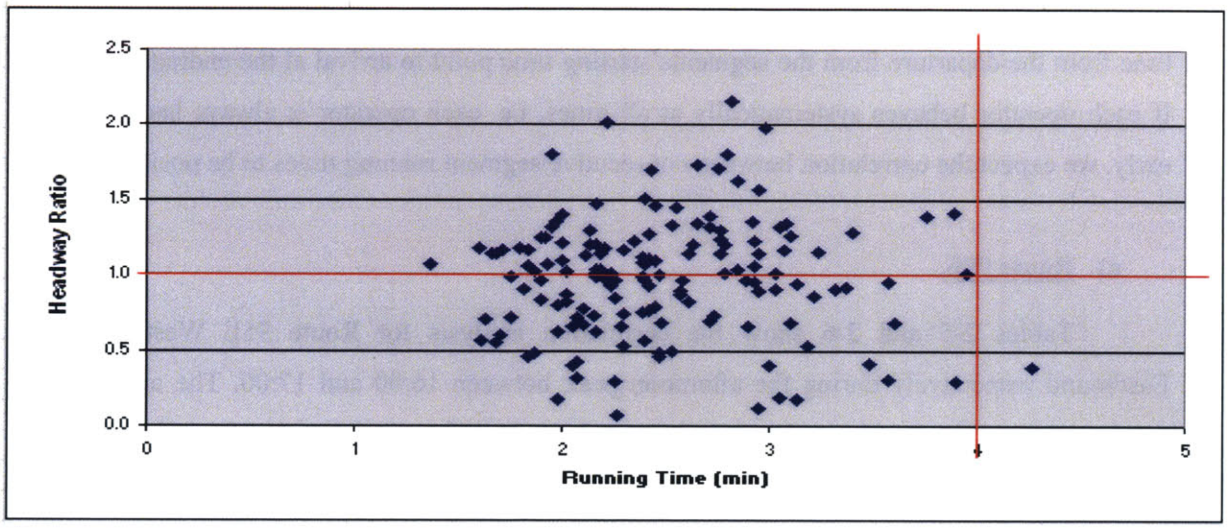

Figure 2-5 Headway Ratio vs. running time for LakCen – ChiCen

Dots representing data points in Figures 2-4 are slightly less scattered than those in Figure 2-5 because the correlation between the headway and the running time is slightly stronger on HsnCen-LakCen than on LakCen-ChiCen. On both these segments, the correlation is positive; as the headway increases, the running time tends to increase. We note that the running times in Figure 2-5 are significantly smaller than the scheduled running time. This may help explain why there is no correlation between the headway and the running time on that segment.

Because of the small correlation between the headways and the running times, we can safely assume that the running times are independent of the headways on both Routes 95E and 85.

On these two routes, the hypothesis seems reasonable. However, this hypothesis is unlikely to be valid in all cases, especially on heavy routes. So while the model is clearly applicable to the two routes of immediate interest, similar tests should be performed to see if this relatively simple model is applicable elsewhere. If not a more complex model will be required, as discussed in Chapter 6.

2.2.2. Relationships between Running Times on Consecutive Segments

This hypothesis suggests that there is no correlation between the running time for a specific bus on one segment and its running time on the previous segment. If this hypothesis is correct, it means that operator-specific behavior such as operators who are always late or always early is unimportant. This hypothesis is tested empirically for CTA Routes 95E and 85 with a correlation analysis between consecutive segment running times. The segment running time is the time from the departure from the segments'starting time point to arrival at the ending time point. If each operator behaves systematically at all times, i.e. each operator is always late or always early, we expect the correlation between consecutive segment running times to be positive.

a) <u>Route 95E</u>

Tables 2-5 and 2-6 show the correlation analysis for Route 95E Westbound and Eastbound respectively during the afternoon peak between 16:00 and 17:00. The analysis was conducted for eight operators who each drove at least four times in the period from September 25 to October 20, 2006.

	Correlation Coefficient R between Running Time with the previous segment	Determination Coefficient R^2
92 Buf – 92 Com		
92 Com – 94 Sto	0.058	0.34%
94 Sto – 93 Cot	0.326	10.6%
93 Cot – 95 Red	-0.230	5.4%

Table 2-5 Running Time – Running Time analysis for Route 95 Westbound [5]

[5] The operators who drove at least 4 times in the 20 weekdays sampled

	Correlation Coefficient R between Running Time with the previous segment	Determination Coefficient R^2
95 Red – 93 Cot		
93 Cot – 94 Sto	0.199	4.0%
94 Sto – 92 Com	-0.034	0.1%
92 Com – 92 Buf	0.019	0.04%

Table 2-6 Running Time – Running Time analysis for Route 95 Eastbound

From Tables 2-5 and 2-6, we note that generally the correlation is small but positive; operators do indeed tend to drive fast or slow. There are two segments, one Westbound and the other Eastbound, where the correlation seems stronger than on the other segments. The running time on the Westbound 92 Com – 94 Sto segment explains 10% of the variation of the running time on the 94 Sto – 93 Cot segment and the correlation is positive; if an operator is slow on 92 Com – 94 Sto, he tends also to be slow on 94 Sto – 93 Cot. There are two mains reasons for this correlation:

- there is not enough running time scheduled on segment 92 Com – 94 Sto; the scheduled running time is set at the 53^{th} percentile of the cumulative running time distribution,

- 92 Com – 94 Sto is the heaviest Westbound segment during this hour; with an expected hourly passenger arrival rate of 137 passengers. Thus, when a vehicle arrives late, it has to pick up more passengers, and the load will increase, requiring more time to handle passengers at the following stops of the route and consequently increasing the running time on the following segment 94 Sto-93 Cot.

Eastbound, the correlation between the segments 95 Red-93 Cot and 93 Cot-94 Sto is the strongest with running time on 95 Red – 93 Cot explaining 4% of the variation of the running time on 93 Cot-94 Sto. This is due to the fact that most Eastbound boardings occur on the first two segments of the route, 95 Red – 93 Cot and 93 Cot – 94 Sto. Thus, when the running time is longer on the first segment, running times will also be longer on 93 Cot – 94 Sto because more passengers will be waiting to board the bus resulting in longer dwell times and hence longer segment running times.

Figures 2-6 and 2-7 show the running times on consecutive segments for the segments which have the highest correlation, 92 Com – 94 Sto and 94 Sto – 93 Cot, and the lowest correlation, 93 Cot – 94 Sto and 94 Sto – 92 Com, respectively.

We observe that the data points are less scattered in Figure 2-6 than in Figure 2-7, Measurements on Figure 2-6 line up, evidence of some positive correlation between the running time on 92 Com-94 Sto and on 94 Sto-93 Cot. However, we observe that the running time on 92 Com-94 Sto is always shorter than the schedule and there is no strong correlation.

In summary, the running time on a segment explains at most 10.6% of the running time variation on the following segment. Therefore, on Route 95E, we can safely assume that running times on consecutive segments are independent.

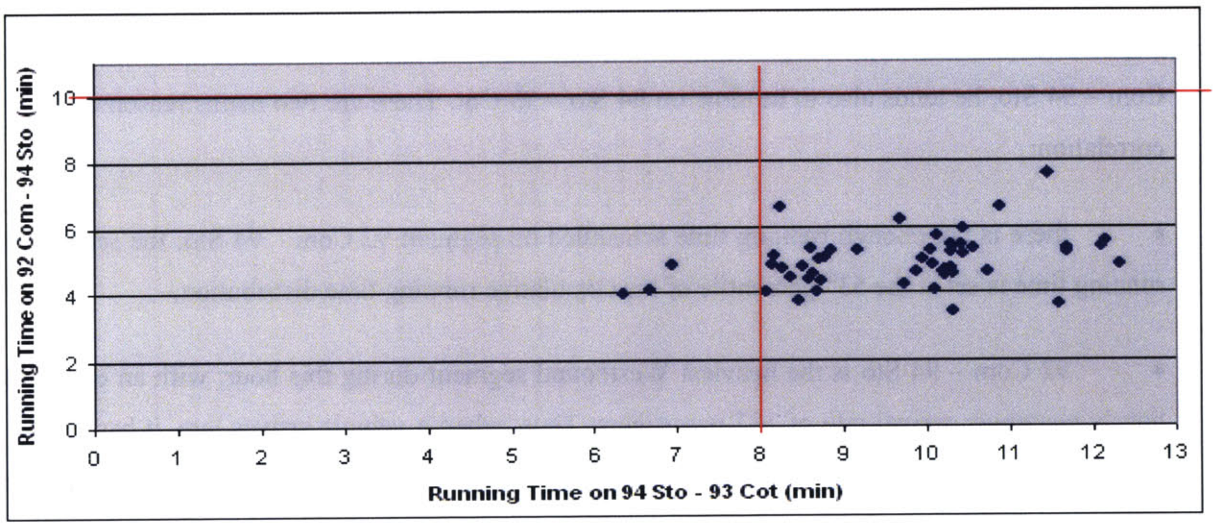

Figure 2-6 Running Times on 92 Com – 94 Sto vs. 94 Sto – 93 Cot

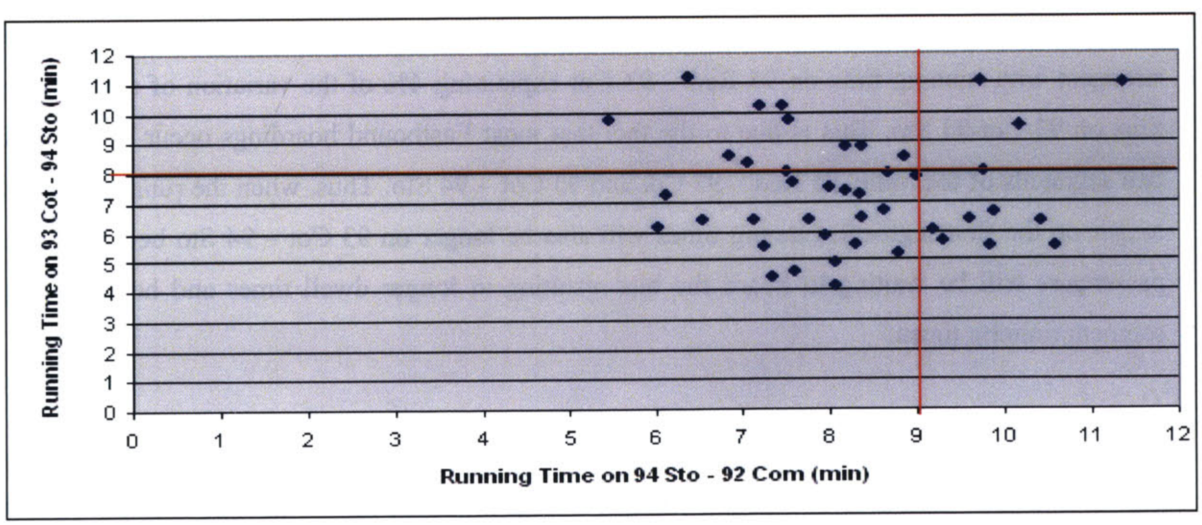

Figure 2-7 Running Times on 93 Cot – 94 Sto vs. 94 Sto – 92 Com

b) Route 85

Tables 2-7 and 2-8 show the correlation analysis for Route 85 during the morning peak between 7:00 and 8:00. The analysis was conducted for twelve operators each of whom drove at least four times in the period from April 24 to May 19, 2006.

	Correlation Coefficient R between Running Time with the previous segment	Determination Coefficient R^2
Bm Els-JpkBlu		
JpkBl2-IrvCen	-0.01	0.02%
IrvCen-BelCen	-0.29	8.63%
BelCen-FulCen	0.04	0.19%
FulCen-NorCen	0.03	0.06%
NorCen-ChiCen	0.33	11.04%
ChiCen-LakCen	0.25	6.32%
LakCen-HsnCen	0.33	11.07%

Table 2-7 Running Time – Running Time analysis for Route 85 Southbound

	Correlation Coefficient R between Running Time with the previous segment	Determination Coefficient R^2
HsnCen - LakCen		
LakCen - ChiCen	0.06	0.35%
ChiCen - NorCen	0.01	0.02%
NorCen - FulCen	-0.15	2.14%
FulCen - BelCen	0.07	0.52%
BelCen - IrvCen	-0.04	0.14%
IrvCen - JpkBlu	-0.15	2.39%
JpkBlu - Bm Els	0.19	3.69%

Table 2-8 Running Time – Running Time analysis for Route 85 Northbound

From Tables 2-7 and 2-8, we note that most of the time the correlation is weak but positive; as with Route 95E. There are two Soutbound segments with stronger correlation. The running time on the FulCen – NorCen segment explains 11% of the running time variation on the NorCen – ChiCen segment. This is because most boardings Southbound occur on the segment NorCen – ChiCen. This segment has an expected hourly passenger arrival rate of 66 passengers. Thus, when the running time is longer on FulCen – NorCen, the running time on NorCen – ChiCen also tends to be longer because the bus arrives later on that segment where more passengers will have been waiting due to the lateness of the bus. Consequently, the dwell time and the running time will also be longer. Likewise, the running time on the ChiCen – LakCen segment explains 11% of the running time variation on the LakCen – HsnCen segment. This is due to the fact that most Southbound alightings occur on the LakCen – HsnCen segment.

Figures 2-8 and 2-9 show the running times on consecutive segments for the segments which have the highest correlation, ChiCen - LakCen and LakCen - HsnCen, and the lowest correlation, LakCen - ChiCen and ChiCen - NorCen, respectively.

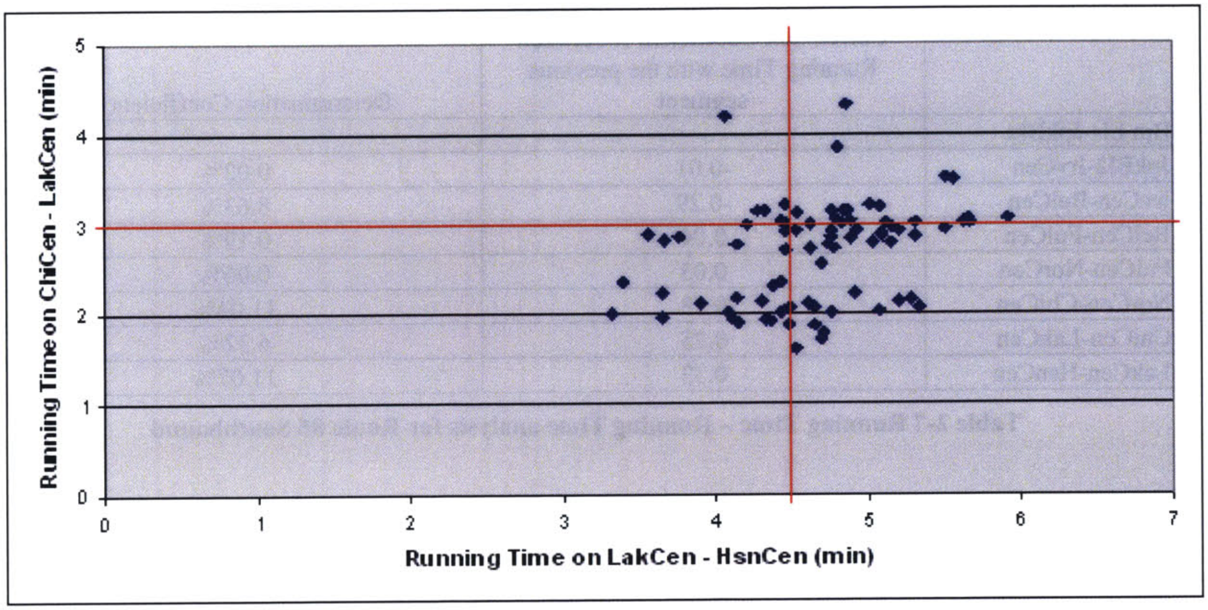

Figure 2-8 Running Time for ChiCen-LakCen vs. running time for LakCen-HsnCen

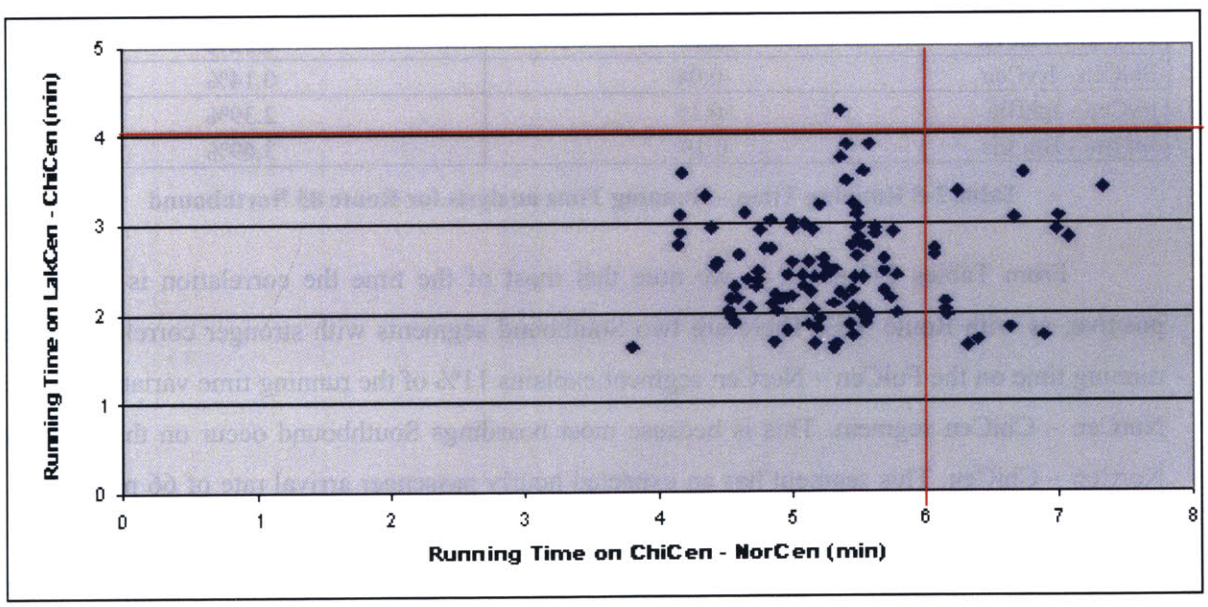

Figure 2-9 Running Time for LakCen-ChiCen vs. running time for ChiCen-NorCen

We observe that the data points in Figure 2-8 are less scattered than those in Figure 2-6 because the correlation is more significant between the ChiCen-LakCen and LakCen-HsnCen segments than between the 92 Com94 Sto and 94 Sto-93 Cot segments. We also note that the correlation is positive in Figures 2-8 and 2-9; as the running time increases on the first segment, it also increases on the second segment.

Because of the small correlation between headways and running times, we can reasonably assume that the running times on consecutive segments are independent on both Routes 95E and 85. While on these two routes the hypothesis holds it is unlikely to be valid in all cases and should be tested, as noted previously, before using the model elsewhere.

2.2.3. Other assumptions used in the model

a) <u>The passenger arrival rate is constant over the peak hour</u>

This assumption is reasonable on high-frequency bus routes (i.e., routes whose headway is less than ten-fifteen minutes) since passengers are generally believed to arrive randomly at stops and do not time their arrival according to the bus schedule. Moreover, the reliability and passenger service quality of Routes 95E and 85 will only be studied during the peak hour during which it can be assumed that the passenger arrival rate does not vary significantly.

b) <u>All passengers can board the first bus.</u>

This assumption is generally reasonable in agencies such as the CTA since operators are instructed not to pass passengers waiting at stops. If a passenger is passed by a bus, he can report it to customer service and the operator will be sanctioned. The operator should stop and allow passengers to attempt to board at every stop where passengers are waiting even if the bus is full. However, there is still a possibility especially during peak hours that passengers cannot board the bus and have to wait for the following one. In this case, this assumption will result in the model's underestimation of passenger waiting time.

During peak hours, the average load is never larger than 21 passengers on Route 95E and 27 passengers on Route 85. Consequently, this assumption seems reasonable for both routes.

c) **<u>The schedule-based holding control strategy is enforced.</u>**

Operators are assumed to hold at time points (or terminals) until the scheduled departure time if they arrive early at time points and if they arrive late they will depart immediately after letting passengers board and alight. Furthermore, we will not consider the cases where operators (i) "drag" on streets rather than hold at time points if they know that there is too much scheduled running time on a segment, (ii) depart time points early and (iii) depart time points late if they could have departed on-time. When operators "drag" on streets instead of holding at time points, it increases running variability because all operators do not behave consistently and consequently this increases headway variability which triggers unreliability. Consequently, by assuming that operators do not kill time en route but hold at time points, the model may underestimate the headway variability and unreliability. This final assumption further implies that there is strict on-time departure enforcement, i.e. operators leave terminals on-time at the beginning of the day. However, in real operation, operators do not always follow the rules. For example, they do not necessarily always hold buses to improve bus service reliability. Some experienced operators sometimes tend to maintain bus service reliability by other self-monitoring methods. Also some lazy operators may drive faster to try to bunch with the preceding bus. However, this assumption implies that all operators use the same self-monitoring measure to improve bus service reliability. This could become the case with sufficient operator training, supervision and enforcement.

d) **<u>The scheduled segment running time does not affect the running time distribution</u>**

This assumption implies that the segment running time distributions (from departure from the starting time point to arrival at the next time point) obtained from the AVL data are not influenced by specific operator behavior in reaction to the amount of scheduled running time on a segment and that they are unconstrained distributions. The only way to guarantee unconstrained segment running time distributions would be experimentally, i.e. by instructing operators to run as fast as possible on the route. Such an experiment was not possible in our case, so we have to assume that the observed AVL distribution is unconstrained.

This assumption simplifies the problem, but it may not be correct in all cases. We know that operators sometimes kill time en route instead of holding at time points. Consequently, some measurements of the running time distributions obtained from the AVL data are slightly shifted to the right compared to the unconstrained running time distribution. In the case where the schedule tested does not allocate enough running time on a segment, this assumption may overstate the passenger waiting time on the segment. Indeed, the running time variability created by "dragging" on streets by some operators will also affect the headway variability. However, should the tested schedule allocate enough running time on a segment, this assumption will not affect the assessment of the passenger waiting time (because we also assume schedule-based holding is enforced). In both cases, the assumption may slightly overstate the in-vehicle travel time on the route. We expect the overestimations, which will be consistent across the several schedules tested, to be small. Therefore this assumption is reasonable.

To summarize, we have shown that the hypotheses and assumptions are reasonable for the CTA Routes 95E and 85, but are unlikely to be valid in all other cases. So the model is clearly applicable to the two routes of immediate interest, however, similar tests to those described above should be performed before applying the model to other routes. Chapter 6 will discuss a more complex model which could be used on routes which do not satisfy the above hypotheses and assumptions.

2.3. Model Description

This section presents the model in detail. Section 2.3.1 focuses on the running time component of the model. Section 2.3.2 explains how the model deals with recovery time. Finally section 2.3.3 presents the way the model derives the cost.

2.3.1. Running Time

On high-frequency bus routes, since passengers are assumed to arrive randomly at stops, reliability for passengers depends on the actual headway. The actual departure headway is the time between the departures of consecutive trips from time point i. When the headway is variable, passengers experience poor service. When the scheduled segment running times allow a high percentage of buses to leave each time point on-time, most headways at each point will be close to the scheduled headway. But when the scheduled segment running time only allows a small percentage of buses to leave the time point on-time, bus headways will tend to be either longer or shorter than scheduled. Thus, reliability will be poorer for passengers waiting on the following segment as well as further down the route. In addition, with inadequate recovery time, unreliability is more likely to propagate from one run to another throughout the day.

Consequently, to assess the reliability of a new schedule, we need to model the actual headway resulting from a proposed schedule. In this section, we discuss how the segment's scheduled running time and headway will affect the variability of the headway at each time point when a schedule-based holding strategy is enforced.

The inputs to the running time model are:

- AVL data to build the segment running time distributions and cumulative density functions
- APC data to compute the average load and passenger arrival rate on each segment
- Number of buses in operation
- Scheduled segment running times
- Scheduled headway
- Number of minutes of recovery time to allocate at each end of the route

The outputs of the running time model are:

- The headway coefficient of variation departing and arriving at each time point on the route
- The mean running time on each segment
- The mean time the vehicles spend on each segment

The headway coefficient of variation, mean segment running time and mean time the vehicles spend on each segment will be used to calculate the passenger waiting and in-vehicle time costs, final outputs of the model.

The running time model will be illustrated on the following route which has n time points:

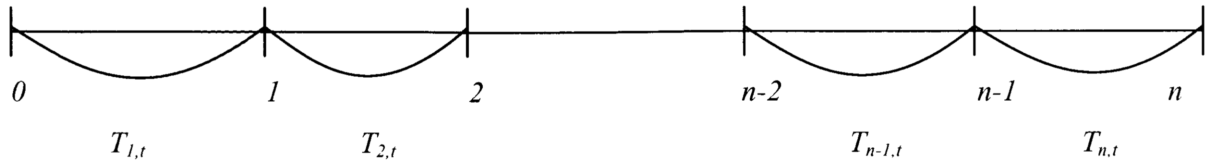

Figure 2-10 Route with n Time Points

With:

$T_{i,t}$= *running time on segment i, for trip t, i.e time between departure from time point i-1 and arrival at time point i.*

BT_i = *actual time the vehicle spends on segment i, i.e. from departure from time point i-1, to departure from time point i*

$DT_{i,t}$ = *dwell time at time point i, for trip t*

$A_{i,t}$ = *actual arrival time at time point i, for trip t*

$S_{i,t}$ = *scheduled departure time from time point i, for trip t*

$D_{i,t}$ = *actual departure time from time point i, for trip t*

For each route segment, the scheduler selects the percentage of vehicles which will be able to complete the segment within the scheduled running time. Each scheduled segment running time is then computed as explained in step 1 of the step-by step process in section 2.1 and specifically Figure 2-1.

The same schedule is assumed throughout the day from the pull out to the analysis hour. For the first trip of the day, we assume an on-time departure from the terminal and the departure time at time point 0, $S_{0,1}$, is set to 0. We also assume that the same buses are used throughout the day. The scheduled departure time from time point 0 for any trip *t* is the sum of the scheduled headway and scheduled departure time of the previous trip, *t-1*, from time point 0.

The scheduled departure time from time point *i* for trip *t* is easily computed once the scheduler proposes a schedule to test. Thus the scheduled departure time from time point *i* is the sum of the scheduled departure time from the previous time point, time point *i-1,* and the scheduled running time on segment *i.* The scheduled running time on segment *i* is the time scheduled for the departure time from time point *i-1* to the departure time from time point *i.*

The schedule does not constrain the time the vehicle spends on the segment or the time point arrival time since the running time, $T_{i,t}$, is a random variable drawn from a segment running time distribution obtained from the AVL data. However since we are enforcing a schedule-based holding strategy, the schedule will be a constraint on the departure time from each time point. The running time on a given route segment, $T_{i,t}$, is measured from the departure from time point i to the arrival at the next time point. The running time on each segment is a random variable which is drawn from the segment running time distribution obtained from the AVL data. We have demonstrated in the previous section that, at least on the routes of interest: (i) the headway variability does not affect the segment running time and (ii) the running time on the preceding segment does not affect the running time on the following segment.

The arrival time at time point 1 is the sum of the scheduled departure time from time point 0 and the running time on segment 1. However, for the first trip of the day, since the scheduled departure time from time point 0 is set to 0, the arrival time at time point 1 is equal to the running time on segment 1. The arrival time at time point 1 of all the vehicles which depart terminal 0 for the first trip of the day is the sum of the scheduled departure time and segment running time on segment 1. Indeed, we assume that the first trips of the day leave the terminal perfectly on time. The arrival time at any time point i of the route for any trip t of the day is the sum of the departure time from the previous time point and the running time on the segment.

As stated previously, since we are enforcing a schedule-based holding strategy, the schedule will be a constraint on the departure time from each time point. When operators arrive at time points after the scheduled departure time, they are assumed to leave as soon as they have handled their passengers, but they would hold until the scheduled departure time if they arrive at the time point early. Consequently, the departure time for any trip t from a given time point i is either:

a. The scheduled departure time if the bus arrived and processed the passengers earlier than the scheduled departure time at the time point,

b. Otherwise, the arrival time plus the dwell time.

$$D_{i,t} = S_{i,t} \qquad if\, A_{i,t}+DT_{i,t}<S_{i,t}$$

$$= A_{i,t}+DT_{i,t} \qquad if\, A_{i,t} \geq S_{i,t} \quad (2\text{-}1)$$

This expression also holds for the departure time from either terminal. The departure time in the reverse direction will be the scheduled departure time if the bus arrived and processed the passengers at the terminal earlier than the scheduled departure time from the terminal. Otherwise the departure time is the sum of the arrival time and passenger processing time at the terminal.

From arrival and departure times at each time point, one can calculate the time the bus spends on segment *i*, BT_i, and the segment running time $T_{i,t}$, outputs of the model. They are important since BT_i is the time through passengers spend on the segment and $T_{i,t}$ is the time passengers who get off at *i* spend on the segment. Indeed, passengers seldom experience the scheduled running time. The actual time the bus spends on segment *i* reflects the service delivered on the given segment *i*. The mean time the vehicle spends on segment *i* is the mean of the difference between the departure time from time point *i* and the departure time from time point *i-1*, for all trips *t*.

Since the first trips of the day are assumed to leave the terminal on time; the departing headway at the terminal is equal to the scheduled headway. The departing headway coefficient of variation at each of the following time points of the route is an output of the model. The departing headway at time point *i* for trip *t* is the difference between consecutive vehicle departure times. The arriving headway at time point *i* for trip *t* is the difference between consecutive vehicle arrival times. Consequently, the departing headway coefficient of variation from each time point, as well as the arriving headway coefficient of variation at each time point can be derived.

2.3.2. Recovery Time

Recovery time at the end of a trip has two main purposes:

- It allows buses to get back on schedule if they are late
- It allows operators to get a few minutes break from driving

Recovery time is important since the number of buses able to depart their next trip on-time increases with an increase of recovery time. If more buses can depart their next trip on-time, the headways should be closer to scheduled. On the other hand, if a bus arrives later than the scheduled half cycle time (scheduled running time plus scheduled recovery time), the operator cannot take any recovery time and should depart as soon as passenger processing at the terminal is complete. Recovery time thus directly affects the evenness of vehicle headways and is critical to maintaining reliable service.

In order to maintain a good level of reliability, the recovery time should be set so that at least 90 percent of the buses can run the one-way trip within the scheduled half cycle time. In this case, less than 10 percent of the buses will be unable to depart the terminal on time after the first trip of the day although this percentage will increase for subsequent trips if the same buses are operating, although reliefs are scheduled to reduce this effect. If the recovery time is increased so that 100% of the buses can depart on-time, there will be a high cost to the agency in terms of number of buses, or a high cost for the passengers because the frequency of the service will have to be decreased if the number of buses is held constant.

However, since the analyst chooses the scheduled headway and number of buses in the model, the recovery time is necessarily an output. The scheduled recovery time is the difference between the scheduled round trip time and the sum of the scheduled running times for all route segments:

Scheduled recovery time

$$= \textit{Scheduled round-trip time} - \sum \textit{scheduled segment running times in both directions} \quad (2\text{-}2)$$

Furthermore, the scheduled round-trip time is the product of the scheduled headway and number of buses used:

$$\textit{Scheduled round-trip time} = \textit{scheduled headway} * \textit{number of buses scheduled} \quad (2\text{-}3)$$

The scheduled running time on segment i is the time scheduled from the departure from time point $i-1$ to the departure from time point i which includes a possible hold at time point i.

The recovery time computed by the model is the recovery time for both directions. The user then allocates the recovery time between ends of the route. As noted earlier, the recovery time is also a time when the operators can take a break from duties which are often very stressful and tiring. For reasons of safety and morale, operators need a minimum break between trips so that they can maintain their focus on driving. Consequently, it is common to allocate at least 5 minutes of actual recovery time at one of the terminals. It is important to give 5 minutes of actual recovery time and not of scheduled recovery time because the actual recovery time is what operators really experience at terminals. If the bus is late they will experience less recovery time.

The actual recovery time can be derived using the running time model presented in the previous section. It is the difference between the actual departure time and the actual arrival time at the terminal n. The actual departure time from the terminal is the scheduled departure time from the terminal if the bus arrives at the terminal before the scheduled departure time from the terminal. It is the arrival time at terminal plus some time to handle passengers at the terminal if the bus arrives after the scheduled departure time.

The model uses the following policies to establish the recovery time:

- Schedule recovery time at each terminal so that at least 90% of the trips can complete the scheduled one-way trip within the scheduled trip time plus scheduled recovery time
- Allocate at least 5 min of actual recovery time at one of the two terminals

Typically, more recovery time should be scheduled for the direction which has more running time variability in order to guarantee that 90% of the trips in both directions can be completed within the allowed time.

Also, since the model has a cost component, the model will help the scheduler in determining which end of the route needs more recovery time according to the demand by direction on the route; more recovery time is needed before vehicles start the heavier direction of the route.

2.3.3. Costs

The cost component of the model is used to assess the cost of a given schedule in terms of passenger waiting and in-vehicle time costs as well as operating cost. The advantage of this approach is that it translates service quality into a cost which allows easier combination of passenger impact and transit agency cost.

To evaluate a proposed schedule, three costs need to be estimated:

- The expected passenger waiting time
- The expected in-vehicle travel time
- The operating cost

Each of these three costs will be computed per hour of operation as explained below:

a) **Passenger waiting time cost**

The expected waiting time for a passenger arriving randomly at point *i*, under the assumption that the vehicle capacity is not constraining, is (Welding, 1957, Holroyd and Scraggs, 1966, and Osuna and Newell, 1972):

$$E(W_i) = \frac{E(H_i)}{2}\left[1 + \frac{V(H_i)}{E(H_i)^2}\right] = \frac{E(H_i)}{2}(1 + COV(H_i)^2) \tag{2-4}$$

where,

$E(W_i)$ = *expected waiting time per passenger at point i*

$E(H_i)$= *expected headway at point i*

$V(H_i)$= *headway variance at point i*

$COV(H_i)$= *coefficient of variation of headway*

However, this expression cannot be directly applied to our model since we are working at the segment level whereas the boardings occur at the stop level. Consequently, we make the following two assumptions: (1) boardings are uniform over the segment and (2) all the passengers on the segment experience a headway variability equal to the average at the start and end of the segment. These assumptions will underestimate the passenger waiting time cost if most boardings occur towards the end of the segment, but will overestimate the passenger waiting time cost if most boardings occur towards the start of the segment. The expected hourly passenger waiting time cost at time point *i* is then:

$$E(C_{w_i}) = \frac{\gamma_w}{60} * \frac{E(H_i)}{2} * \left(1 + \frac{COV(DH_i)^2 + COV(AH_{i+1})^2}{2}\right) * q_i \tag{2-5}$$

where,

$E(C_{Wi})$= *expected hourly waiting time cost at time point i*

γ_ω = *waiting time cost per passenger hour*

$E(H_i)$= *expected headway at time point i*

$COV(DH_i)$ = *coefficient of variation of headway leaving time point i*

$COV(AH_{i+1})$ = *coefficient of variation of headway arriving at time point i*

q_i = *hourly passenger arrival rate at time point i*

b) Passenger in-vehicle time cost

The expected in-vehicle travel time of a passenger who is on-board throughout segment i, is the expected time the bus will take from departure from time point, *i-1*, to arrival at time point *i*.

Estimating the expected in-vehicle travel time for passengers who were not on-board throughout the segment presents the following issues: we are working on the segment level whereas the boardings and alightings happen at the stop level and we do not have origin-destination information. Consequently, we make two assumptions:

(1) If the load at the start of the segment equals the load at the end of the segment, we assume that the load was constant throughout the segment, i.e if a passenger alights at a stop, a passenger boards at the same stop and consequently the load is the same. If the load remains the same, the expected in-vehicle travel time cost is simply the product of the load and the expected time the bus will take from the departure from time point *i-1* to arrival at time point *i*.

(2) If the load differs between the start and the end of the segment, the average load on the segment experiences the expected time the bus takes from departure from time point *i-1* to arrival at time point *i*.

With regard to the load, it is not necessary to compute the load at each time point for each trip since we are calculating an expected hourly cost. The expected hourly load at each time point is obtained from Automatic Passenger Count (APC) data.

Lastly, the in-vehicle cost to the through passengers, (i.e., passengers who are not getting off at the last time point of the segment), should also be added to the in-vehicle time cost. These passengers may experience holding at the time point. Therefore, we make two further assumptions. (1) Passengers get off as soon as the vehicle arrives at the time point if it is their final destination. (2) Passengers waiting get on when the vehicle leaves the time point, (i.e. if passengers arrive at the time point while the vehicle is held, they experience waiting time and not in-vehicle travel time). Consequently, the number of through passengers is the lesser value of the arriving load at the time point and the departing load from the time point. These assumptions are only valid at time points and not at terminals where there are no through passengers. Passengers getting off at the terminal will experience only the running time (from the departure at the starting time point of the last segment to the arrival at the terminal).

Thus, the expected hourly passenger in-vehicle travel time cost on segment *i* is:

$$E(C_{D_i}) = \frac{\gamma_D}{60} * \left(E(T_i) * \frac{E(DN_{i-1}) + E(AN_i)}{2} + \left(E(BT_i) - E(T_i)\right) * E(TP_i) \right) \qquad (2\text{-}6)$$

where,

$E(TP_i) = min\ (E(DN_i), E(AN_i)$

where,

$E(C_{D_i})$ = *expected hourly in-vehicle travel time cost on segment i*

γ_D = *in-vehicle travel time cost per passenger hour*

$E(T_i)$= *running time on segment i, for trip t, i.e. time between the departure from time point i-1 to arrival at time point i*

$E(DN_{i-1})$= *expected hourly load departing time point i-1*

$E(AN_i)$=*expected hourly load arriving at time point i*

$E(BT_i)$= *expected actual time the vehicle spends on segment i, i.e. from departure from time point i-1, to departure from time point i*

$E(TP_i)$ = *expected hourly through passengers at time point i*

c) Operating cost

The operating cost includes only the marginal operating cost such as driver wages, fuel, etc. The operating cost is not a function of the model but of the proposed schedule since it is a function of the number of vehicles operating on the route. Thus, the scheduled hourly operating cost is the product of the scheduled number of buses and operating cost per hour of operation:

$$C_{Ov} = \gamma_{Ov} * NBR \qquad (2\text{-}7)$$

where:

C_{Ov} = *hourly operating cost*

γ_{Ov} = *operating cost per hour*

NBR = *number of buses required*

d) Total Cost

The total cost we are seeking to minimize during the time period is:

$$E(TT) = \sum_{i=0}^{n} E(C_{W_i}) + \sum_{i=1}^{n+1} E(C_{D_i}) + C_{Ov} \qquad \text{(2-8)}$$

where:

E(TT) = expected total cost for the time period

$E(C_{W_i})$ = *expected waiting time at time point i*

$E(C_{D_i})$ = *expected in-vehicle travel time cost on segment i*

C_{Ov}= *hourly operating cost*

2.4. Application Process

The analysis process applied in the following applications consists of the following steps:

1. Determine the hourly cost of operation for the current schedule by computing the expected hourly waiting time cost (2-5), the expected hourly in-vehicle travel time cost (2-6) and the hourly operating cost (2-7). The expected hourly passenger cost, which is the sum of the expected hourly waiting time cost and the expected hourly in-vehicle travel time cost, is our upper bound on schedule cost.

2. Compute the cost of the schedules where the same percentile of buses can complete each route segment on time. Thus, compute the costs (waiting cost, in-vehicle travel time cost, operating cost and total cost) of implementing the 10^{th}, 15^{th}, 20^{th},..., 85^{th}, 90^{th} percentile on each segment of the route. The number of buses to use for each schedule will be the minimum number of buses which allow: (i) an actual expected layover of at least 5 minutes at one of the two terminals and (ii) at least 90% of the buses to complete their half cycles within the scheduled times. The cost of the schedule which has the lowest expected hourly passenger cost will be our new upper bound cost. The expected hourly operating cost of the schedule which gives the lowest expected hourly passenger cost will be computed.

3. Investigate different combinations of percentiles on each segment of the bus route in order to find the schedule which minimizes the hourly expected passenger cost with the current number of buses. Set the recovery time such that it allows (i) an actual expected layover of at

least 5 minutes at one of the two terminals and (ii) at least 90% of the buses to be able to run the two one-way trips in a time less than or equal to the two scheduled one-way trip times. Compute the expected hourly operating cost of the schedule which minimizes the total expected passenger cost.

4. Compute the hourly operating cost and the total passenger cost of the schedule found in step 3 with one less bus (if feasible) and one extra bus used on the route.

The results of the last three steps and of the cost of the current schedule will be compared to see whether there is a benefit in implementing the generalized cost minimization process. If there is a benefit, the costs of the schedules obtained in steps 3 and 4 will be less than the costs of the schedule obtained in step 2 of the process. In this case, the agency can benefit from implementing the schedule developed in step 3.

Chapter 3. Chicago Transit Authority Route 95E Application

This chapter investigates the potential for the improved generalized cost minimization process to have a beneficial impact on the reliability of the Chicago Transit Authority (CTA) bus route 95E. Section 3.1 describes CTA Route 95E. Section 3.2 analyses the route during the PM Peak application period. Section 3.3 presents the results of the modeled current situation to confirm the model is producing numbers which are consistent with the data. The result of different scheduling approaches will be presented in sections 3.4 through 3.6. The costs of each approach are compared in section 3.7.

The objectives of this chapter are twofold:

- To provide a practical demonstration of the model
- To investigate the effectiveness of the proposed scheduling process compared with the alternatives

3.1. Route 95E Characteristics

Route 95E was chosen for several reasons:

- It appears to have some segments with too much scheduled running time and others with not enough scheduled running time based on recent AVL data[6],
- It is a high frequency route, i.e. the headways are 10 minutes or less in the peak period,
- It is considered a "key route"[7] in the CTA Service Standards, providing an extra incentive to improve reliability on this route

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[6] End-to-end running time analysis webpage on CTA intranet, Michael Haynes, CTA

[7] "Key" routes and "support" routes define the CTA bus system. Key routes provide the backbone of CTA service. They include the most productive bus routes, plus additional routes to provide basic geographic coverage. Support routes are the remaining routes. They support the rail and key bus network by serving a variety of important specialized functions that all enhance the quality of service and improve market share. Two-thirds of all CTA rides are taken on the bus system. Key bus routes provide nearly half (47%) of all CTA rides. [CTA Service Standards]

3.1.1. Route Description

CTA Route 95E runs five miles East-West on 93[rd] St. and 95[th] St. from Buffalo St. (3332 E) to Lafayette St. (30 W). Route 95 E connects with: the south terminal of the Red Line; 95[th]/ Dan Ryan, two Metra stations and many bus routes serving either the Loop or the South part of the city. A schematic of Route 95E including the connections with the Red Line and the Metra Lines is shown in Figure 3-1. Operators begin and end their runs at 92[nd] St. and Buffalo St, the route's eastern terminus. The CTA provides service throughout the day between Buffalo St. and Lafayette St. except between 23:30 and 4:30.

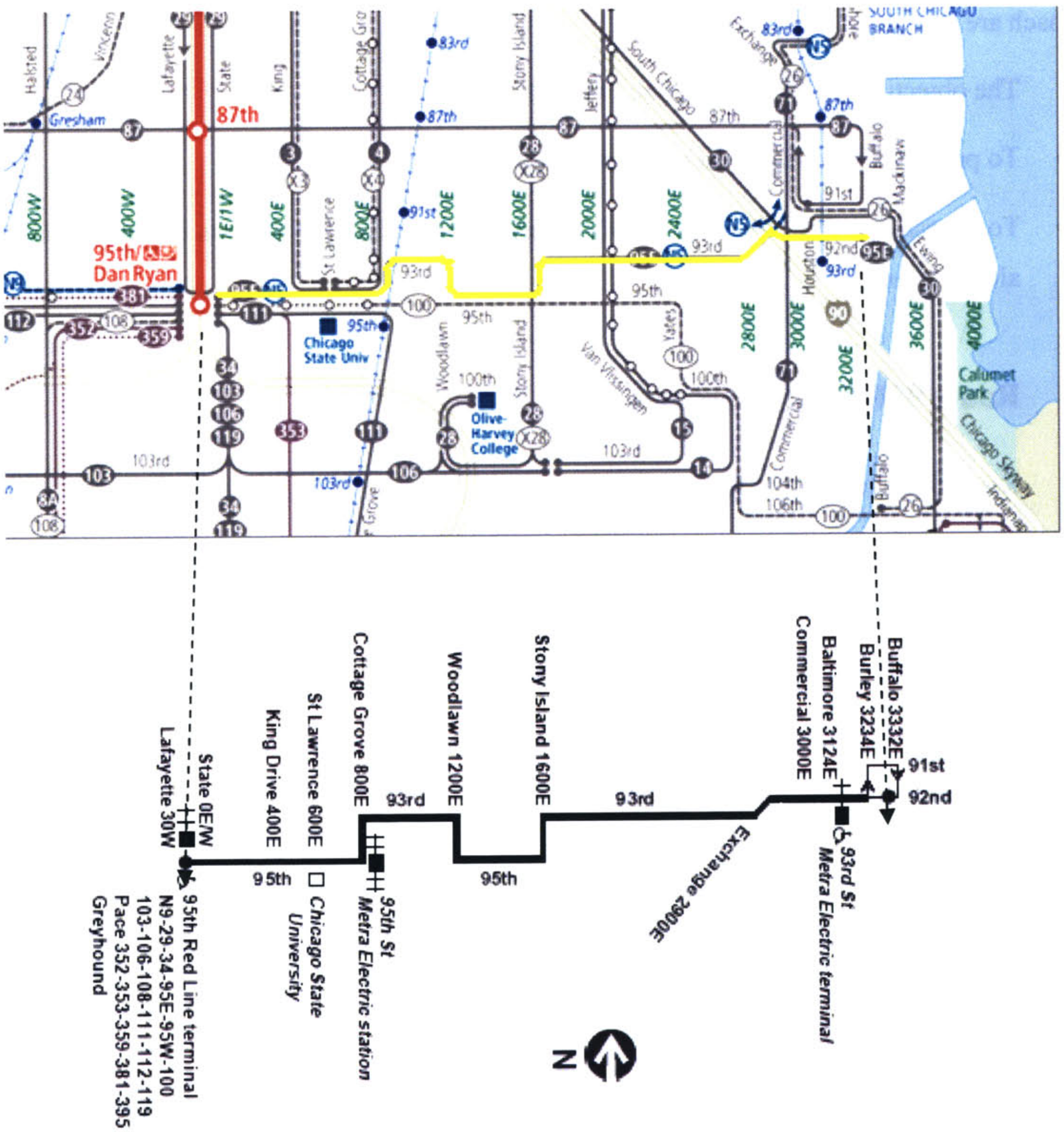


Figure 3-1 CTA Route 95 E

3.1.2. Route Segment Description

There are five time points on the route in each direction. Westbound, the time points are: (1) 92nd St. and Buffalo St. (92 Buf), (2) 92nd St. and Commercial St. (92 Com), (3) 94th St. and Stony Island St. (94 Sto), (4) 93rd St. and Cottage Grove St. (93 Cot) and (5) 95th Street and Red Line terminal (95 Red). The time points are the same Eastbound in the reverse order. The length of each segment defined by these time points is not equal, as Table 3-1 shows.

Route Segment	Length (in miles)
92 Buf – 92 Com	0.4
92 Com – 94 Sto	2.0
94 Sto – 93 Cot	1.4
93 Cot – 95 Red	1.3

Table 3-1 Route Segment Lengths

The distance between the Eastern terminal (92 Buf) and the first time point of the route (92 Com) is very short compared to the other segments. As seen in the literature review, time points should generally be located at stops at or following which the number of boarding passengers is high relative to the number of through passengers. However time points in the CTA bus network have been defined historically and do not necessarily comply with these principles.

3.1.3. Ridership

Figures 3-2 and 3-3 present the average boardings per trip during fall 2006 (from August 28, 2006 to January 2, 2007) throughout a weekday of operation Westbound and Eastbound respectively.

We note that in both directions the number of boardings is highly variable from one trip to the next. This is probably due to bus bunching: when two buses are bunched together, the first bus has many boardings because of the very large gap with its leader, whereas the following bus has fewer boardings. The graphs also indicate that it is often the same trips which are bunched, since the graphs present the average number of boardings per trip over a four-month period. We can conclude that on Route 95E bus bunching often occurs due to specific operator behaviors.

Most boardings occur between 7:00 and 8:00 in the morning and between 16:00 and 17:00 in the afternoon. When boardings in both directions are combined, there are on average 420 passengers boarding between 7:00 and 8:00 and on average 483 passengers boarding between

16:00 and 17:00. During the off-peak, between 10:00 and 14:00, there are on average 270 passengers boarding per hour. This route is not heavily directional since the number of boardings in each direction during the peak hours is similar.

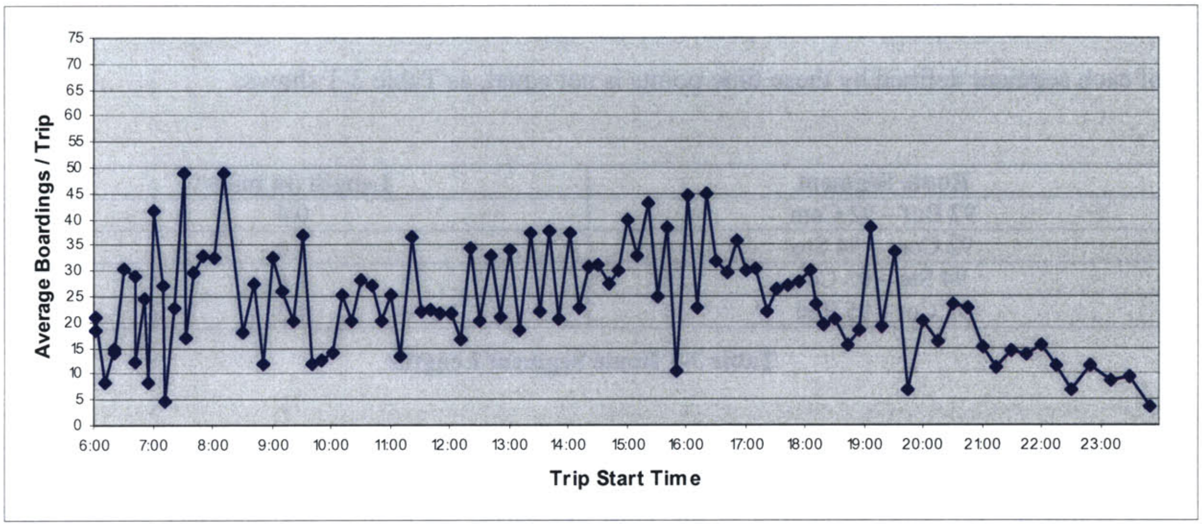


Figure 3-2 Average Boarding/ Trip (Westbound)

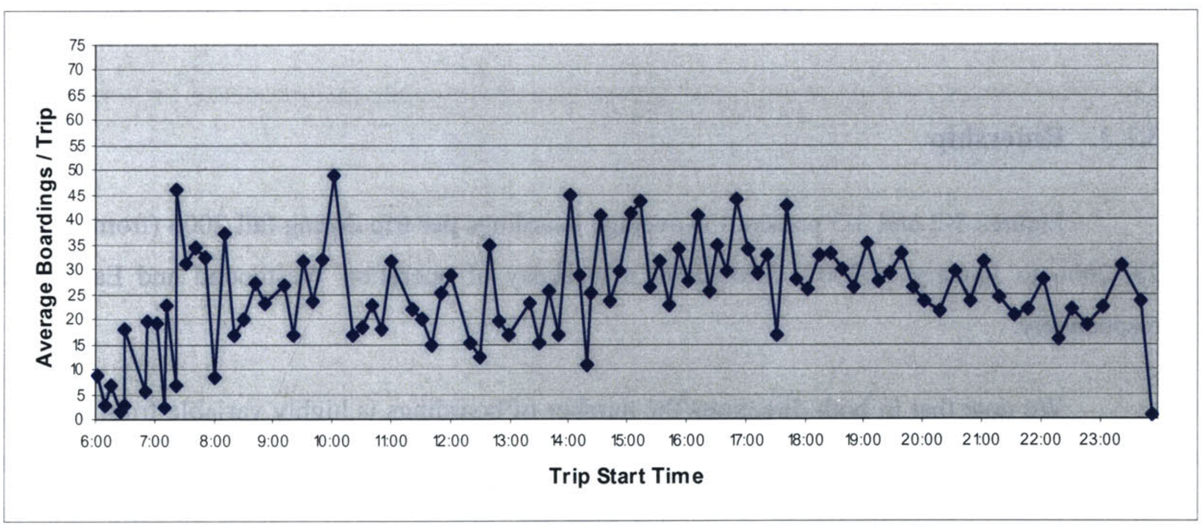


Figure 3-3 Average Boarding/ Trip (Eastbound)

3.1.4. Scheduled Headways

Figures 3-4 and 3-5 show the scheduled (Westbound) headways at 92 Buf and at 95 Red (Eastbound) during fall 2006.

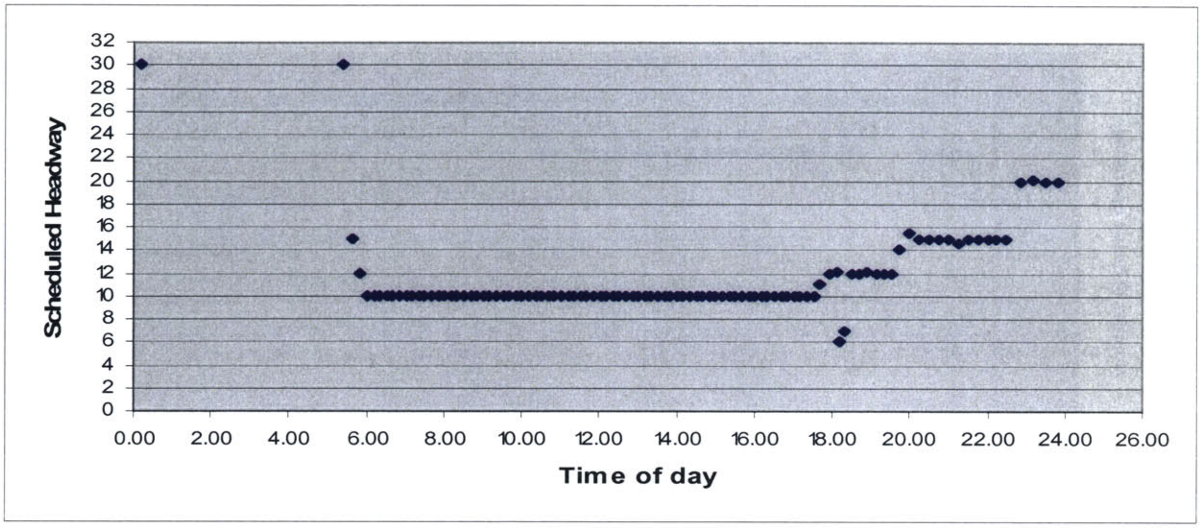


Figure 3-4 Scheduled headway at 92 Buf (Westbound)

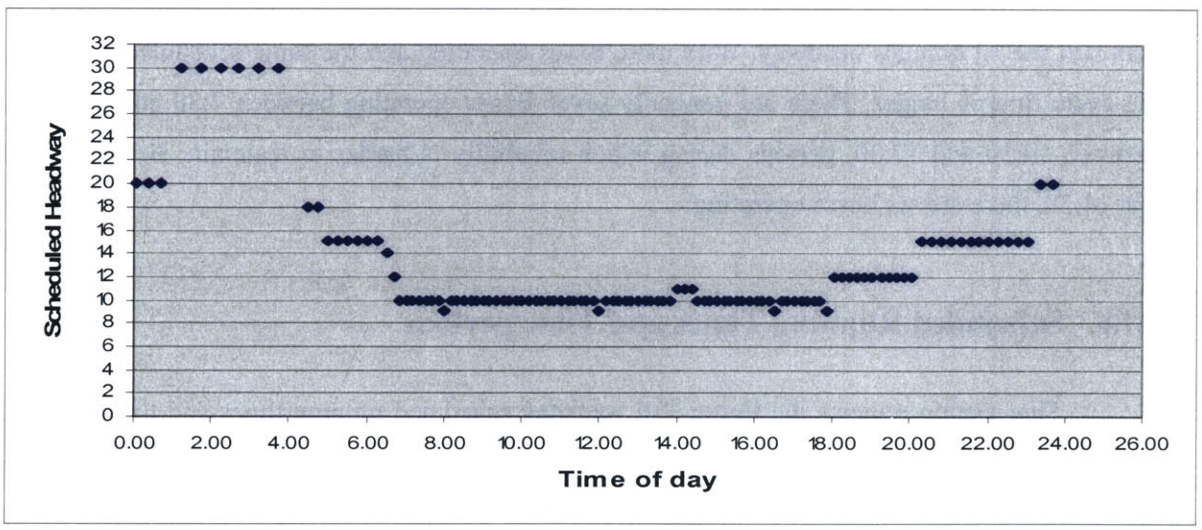


Figure 3-5 Scheduled headway at 95 Red (Eastbound)

Even though the number of boardings varies throughout the day, we note that the scheduled headway is virtually constant at 10 minutes between 6:00 and 18:00.

3.1.5. Number of buses

Figure 3-6 shows the number of buses used throughout the day during fall 2006 based on the supervisor guide produced by Hastus.

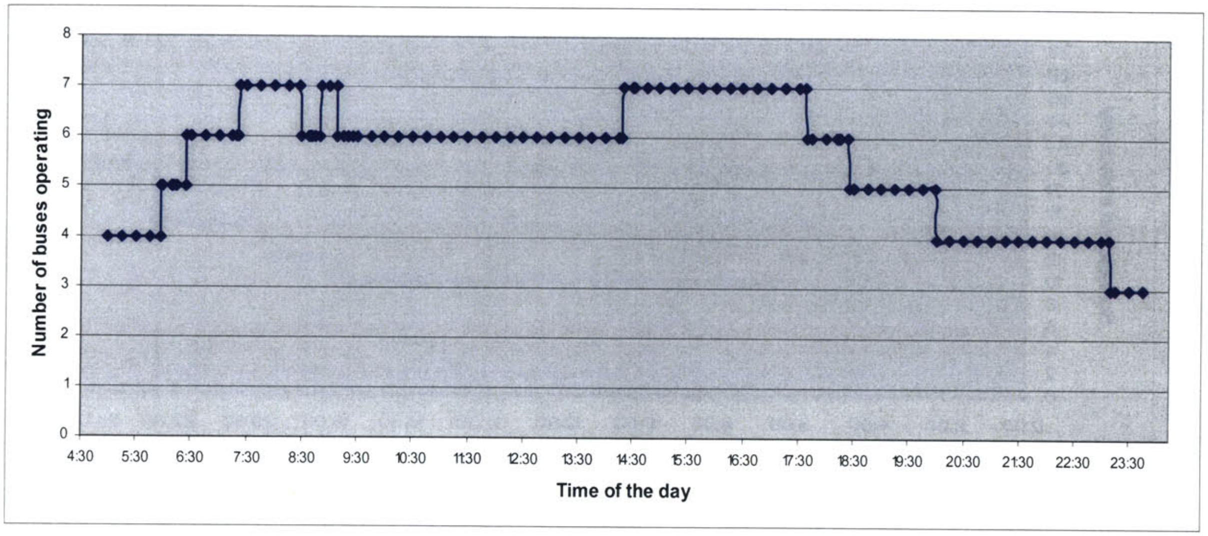


Figure 3-6 Number of buses operating

We note that the number of buses vary and increase during the peak hours in order to maintain the 10 minutes headway. With more buses operating and the same scheduled headway, the cycle time is longer. There are generally seven buses operating between 7:30 and 9:00 and between 14:30 and 17:30, periods during which reliability is harder to maintain. Between 9:00 and 14:30, there are six buses operating.

3.1.6. Scheduled Running Times and Time periods

This section reviews the Route 95E weekday scheduled running times and time periods. A time period is a period of time during which the one-way scheduled running times and the segment scheduled running times on a given route are constant. Typically, several time periods need to be defined so that the schedule remains accurate as passenger demand and the operating conditions (i.e. traffic) vary.

To determine time period and the running time to schedule in each period, CTA uses Hastus ATP [13]. Hastus ATP is a tool which allows a user to import run time data from an Automatic Vehicle Location (AVL) system, display the data graphically and determine scheduled running times and time periods based on statistical criteria.

Hastus ATP determines time periods using the AVL data. The tool defines time periods, beginning with the first AVL measurement of the day, where the data standard deviation is less than a user defined value. Hastus ATP will take the first measurement of the day and will make an initial time period of half an hour. It will then try to extend this time period as much as possible until the standard deviation of the measurements within the extended time period is greater than the standard deviation defined by the user. Following time periods will be defined the same way; by taking the first measurement not included in the preceding time period and extending the time period until the standard deviation of the measurements within the period exceeds the user defined standard deviation. Hastus ATP then defines schedule running times in each time period so that 65 percent of trips can be completed on time. Layover times are defined which allow 90% to 95% of operators to start their next trip on time [22].

Figures 3-7 and 3-8 show a scatter plot of actual running time observations, scheduled running times and time periods for fall 2006 Westbound and Eastbound, respectively. The scheduled running times and time periods were derived using Hastus ATP but using a 2003 dataset which contained fewer observations. Tables 3-2 and 3-3 show the scheduled running time and running time standard deviation for each time period.

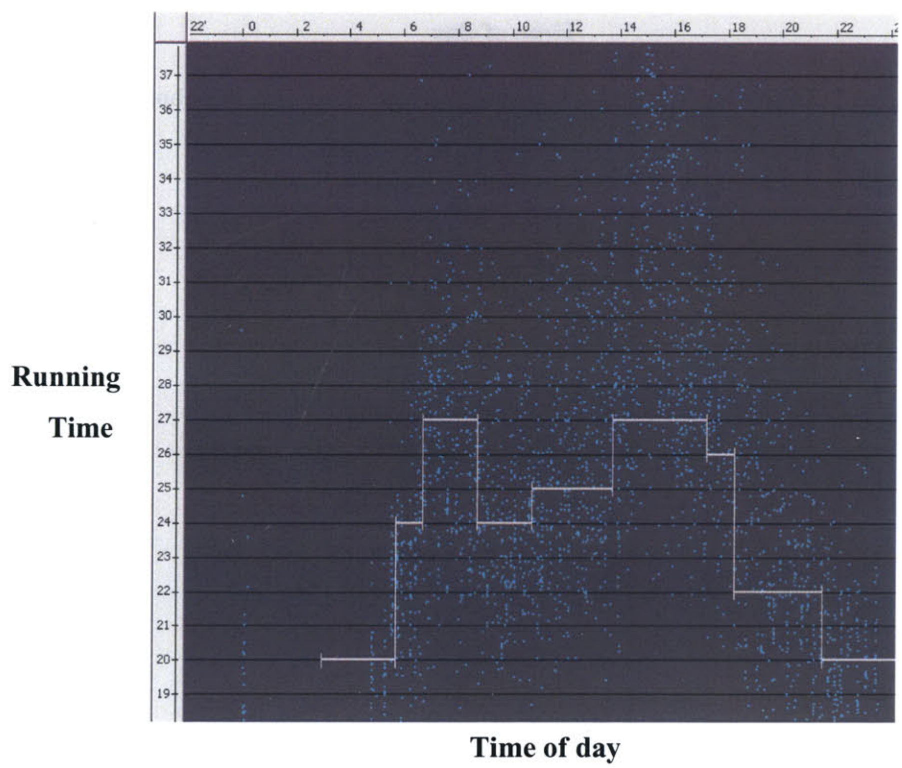
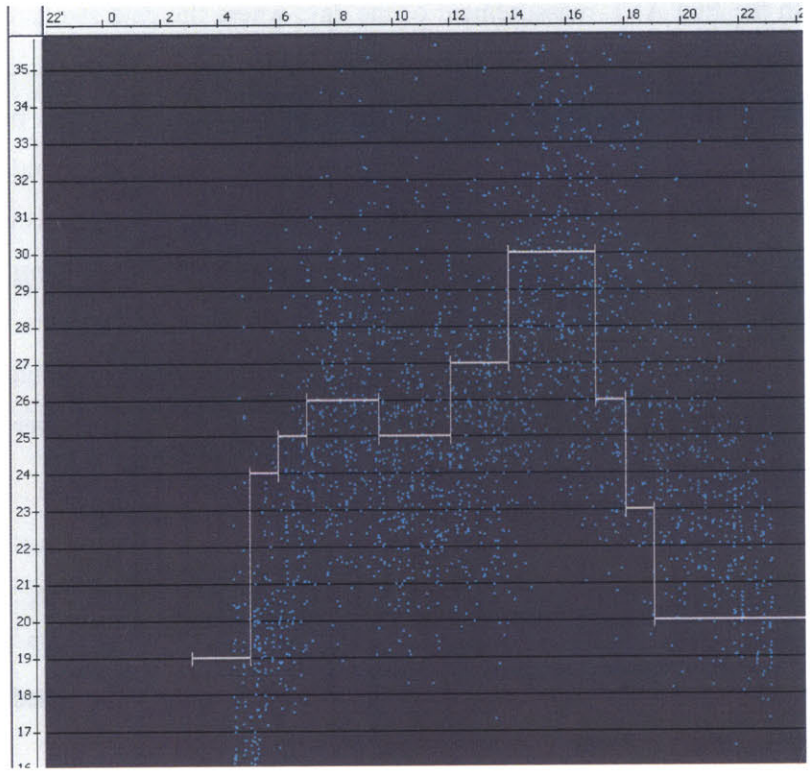


Figure 3-7 Running Time data and scheduled running time (Westbound)[8]

[8] This graph was obtained using Hastus ATP

Running Time



Time of day

Figure 3-8 Running Time data and scheduled running time (Eastbound)[9]

Time Period	Sch. RT	St. Deviation (RT)
6:45 - 8:44	27	3.56
8:45 - 10:44	24	3.16
10:45 - 13:44	25	5.15
13:45 - 17:14	27	6.23
17:15 - 18:14	26	3.59
18:15 - 21:29	22	4.41

Table 3-2 Time Period Statistics (Westbound)

[9] This graph was obtained using Hastus ATP

Time Period	Sch. RT	St. Deviation (RT)
6:00 - 6:59	25	4.0
7:00 - 9:29	26	4.2
9:30 - 11:59	25	4.2
12:00 - 13:59	27	3.3
14:00 - 16:59	30	4.2
17:00 - 17:59	26	4.9
18:00 - 18:59	23	6.4

Table 3-3 Time Period Statistics (Eastbound)

From Figures 3-7 and 3-8 and Tables 3-2 and 3-3, we note that there is significant variation in the running time observations within each time period. Thus, for a route whose scheduled running time in each direction is 30 minutes or less, we observe in some time periods more than a ten-minute range of data, and standard deviations as high as 6 minutes. Having so much running time variability within a time period will affect the headway variability which leads to unreliability. The running time is variable within a time period due to the typical operator behaviors which create bus bunching, as discussed in section 3.1.3. Thus, the running time becomes longer if there are many boardings occurring on one trip but it can be shorter if the bus is bunched with its leader.

During the first half of the day, until 13:45, about half of the trips can be completed within the scheduled running time in both directions. Between 13:45 and 18:15, the majority of the trips cannot be completed within the scheduled running times Westbound, whereas about half of the trips can be completed on time Eastbound. After 18:00, the opposite happens; the majority of the trips cannot be completed within the scheduled running times Eastbound, whereas about half of the trips can be completed on time Westbound. So there is an imbalance in the scheduled running times between the two directions. This leads to running time variability; the time period between 18:00 and 18:59 Eastbound presents the largest running time standard deviation in this direction. When the majority of the trips cannot be completed within the scheduled running time, and if there is not enough layover time scheduled at the end of the trip, unreliability can easily propagate to subsequent trips.

Westbound, there is a single period defined from 13:45 to 17:14. This time comprises part of the off-peak period and part of the peak period. Indeed, we have seen in section 3.1.3 that the off-peak period was between 10:00 and 14:00. However, time periods should be designed to reflect the changes in operating conditions throughout the day. Designing a single time period for two different operating conditions can create significant running time variations during the time period. Indeed, the time period between 13:45 and 17:14 has the largest running time standard deviation of 5.8 minutes Westbound, and this is likely to affect the headway variation which, in turn, triggers unreliability.

3.2. PM Peak Analysis

This section assesses the reliability of Route 95E between 16:00 and 17:00. This hour is selected because it has the most boardings during the PM Peak, as shown in section 3.1.3. We will apply several scheduling approaches to this hour in sections 3.3 through 3.6. In this section, the ridership patterns are reviewed (section 3.2.1) and the running times and headways are discussed (in sections 3.2.2 and 3.2.3 respectively).

We are using one month of Automatic Passenger Count (APC) and Automatic Vehicle Location (AVL) weekday data, from September 25 to October 20, 2006 in this analysis.

3.2.1. Ridership Patterns

a) Westbound

Tables 3-4 and 3-5 show the average hourly Westbound passenger arrivals and load per trip respectively. Table 3-6 computes the ratio of the through passengers at the time point to the number of waiting passengers on the following segment.

	Mean Hourly Passenger Arrivals	Mean Passenger Arrivals per Trip
At 92 Buf	12.9	2.2
On segment 92 Buf - 92 Com	13.1	2.2
At 92 Com	42.9	7.2
On segment 92 Com - 94 Sto	93.6	15.6
At 94 Sto	10.6	1.8
On segment 94 Sto - 93 Cot	24.4	4.1
At 93 Cot	5.1	0.8
On segment 93 Cot - 95 Red	32.4	5.4
TOTAL	**235.8**	**39.3**

Table 3-4 Mean Passenger Arrivals (Westbound)

	Average Load
Leaving 92 Buf	2.2
Arriving 92 Com	4.4
Leaving 92 Com	11.2
Arriving 94 Sto	18.3
Leaving 94 Sto	17.8
Arriving 93 Cot	18.5
Leaving 93 Cot	17.9
Arriving 95 Red	4.8

Table 3-5 Average Load (Westbound)

	Waiting passengers on segment / Through passengers
At 92 Com	5.2
At 94 Sto	0.3
At 93 Cot	0.3

Table 3-6 Ratio of waiting passengers to through passengers (Westbound)

From Table 3-4, we note that in this hour, most of the Westbound boardings occur at 92 Com and between 92 Com and 94 Sto. At 92 Com, transfers occur with bus Route 30 while the area between 92 Com and 94 Sto is a business district. 18% of the Westbound boardings occur at 92 Com and 40% between 92 Com and 94 Sto. The remaining boardings are pretty evenly distributed over the other three segments: 6% on the first segment which includes a Metra station, 10% on the third segment which includes another Metra station and 14% on the final segment of the route. The number of boardings increases as the bus nears the Red Line station.

From Table 3-5, we observe that the Westbound route segments with the heaviest load Westbound are the two last segments 94 Sto-93 Cot and 93 Cot-95 Red. The second segment of the route, 92 Com – 94 Sto, is also quite heavy. The majority of the alightings occur on the last segment of the route which includes the Red Line terminal and connections to many bus routes. However, Table 3-5 also shows that most alightings occur before the Red Line terminal. It is worth noting that most alightings occurring before 95 Red is specific to this hour of operation. Between 15:00 and 16:00 and between 17:00 and 18:00, most alightings occur at the Red Line terminal as would be expected.

From Table 3-6, we observe that the only Westbound segment with a larger number of waiting passengers than through passengers at the time point is 92 Com. At 94 Sto and 93 Cot, the number of through passengers is very large compared to the number of through passengers on the following segments.

b) <u>Eastbound</u>

Tables 3-7 and 3-8 show the average hourly Eastbound passenger arrivals and load per trip respectively. Table 3-9 computes the ratio of through passengers at the time point to waiting passengers on the following segment.

	Mean Hourly Passenger Arrivals	Mean Passenger Arrivals per Trip
At 95 Red	46.7	7.8
On segment 95 Red - 93 Cot	119.8	20.0
At 93 Cot	25.3	4.2
On segment 93 Cot - 94 Sto	19.7	3.3
At 94 Sto	0.0	0.0
On segment 94 Sto - 92 Com	33.8	5.6
At 92 Com	0.0	0.0
On segment 92 Com - 92 Buf	2.3	0.4
TOTAL	**247.8**	**41.3**

Table 3-7 Mean Passenger Arrivals (Eastbound)

	Average Load
Leaving 95 Red	7.8
Arriving 93 Cot	17.0
Leaving 93 Cot	21.2
Arriving 94 Sto	12.3
Leaving 94 Sto	12.3
Arriving 92 Com	5.0
Leaving 92 Com	1.0
Arriving 95 Red	0.9

Table 3-8 Average Load (Eastbound)

	Waiting passengers on segment / Through passengers
93 Cot	0.4
94 Sto	0.5
92 Com	0.4

Table 3-9 Ratio of waiting passengers to through passengers (Eastbound)

During this period, the first segment of the route 95 Red – 93 Cot, accounts for 48% of the Eastbound boardings. On the first segment, we note that most boardings occur after the Red Line terminal where the Chicago State University is located; 19% of the Eastbound boardings occur on that segment. Once again most boardings occurring after 95 Red is specific of this hour of operation which is when many students leave the university. The number of boardings decreases steadily along the route: 18% of the boardings occur between 93 Cot -94 Sto including 10% at 93 Cot, 14% occur on 94 Sto – 92 Com and less than 1% of the boardings occur on the last segment of the route.

Eastbound, the load is the heaviest on the two first segments of the route since most passengers board at the Red Line terminal or on the first route segment. As the bus travels further East, the number of boardings decreases as well as the load.

Table 3-9 shows that the number of Eastbound waiting passengers on each segment is very small compared to the number of through passengers at the preceding time point.

Clearly Route 95E is principally a feeder/distributor route. Westbound, passengers board throughout the route (particularly between 92 Com and 94 Sto) and most of them alight on the last segment of the route which includes the Red Line terminal and connections to many bus routes. Eastbound, passengers board primarily on the first segment and alight throughout the route.

3.2.2. Running times

Tables 3-10 and 3-11 show the running time analysis between 16:00 and 17:00 Westbound and Eastbound respectively. The second column shows the scheduled running times on each segment of the route. The third column computes the percentage of buses which complete the segments (from departing the starting time point of the segment to arriving at the next time point) within the scheduled segment running time. The fourth column indicates the proportion of vehicles which depart the starting time point of each segment on time. The fifth column presents the mean segment running times, from the time point departure to arrival at the next time point. The sixth column shows the coefficient of variation of the running time (from departure to arrival) indicating the segment running time variability. The seventh column shows the mean running time, between departures at successive time points, in order to gauge whether "holding" (i.e., operators waiting at the time point to depart) is occurring at each time point.

Westbound	Sch. RT (min)	% of vehicles which run the segment within the sch RT	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Arrive) (min)	COV RT (From Depart to Arrive)	Mean RT (From Depart to Depart) (min)
92 Buf– 92 Com	2	86%	22%	1.6	0.69	3.7
92 Com –94 Sto	10	53%	9%	9.8	0.18	10.6
94 Sto – 93 Cot	8	98%	9%	5.3	0.18	6.2
93 Cot – 95 Red	7	11%	30%	8.9	0.20	
One-Way RT	27	12%		25.6		29.4
Layover at 95 Red	4					4.3
One-Way Trip	31	24%				33.7

Table 3-10 Running times in the PM Peak (Westbound)

Eastbound	Sch. RT (min)	% of vehicles which run the segment within the sch RT	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Arrive) (min)	COV RT (From Depart to Arrive)	Mean RT (From Depart to Depart) (min)
95 Red – 93 Cot	10 min	92%	0%	7.3 min	0.20	8.1 min
93 Cot – 94 Sto	8 min	53%	10%	8.0 min	0.28	8.3 min
94 Sto – 92 Com	9 min	58%	10%	8.8 min	0.17	10.4 min
92 Com – 92 Buf	3 min	90%	8%	2.4 min	0.75	
One-Way RT	30 min	26%		26.5 min		29.1 min
Layover at 92 Buf	8 min-9min					2.5 min
One-Way Trip	38 min-39min	89% -92%				31.6 min

Table 3-11 Running times in the PM Peak (Eastbound)

We note that the actual mean round-trip "cycle" time is 65.3 minutes and the scheduled round-trip cycle time is 70 minutes for this period. Thus, on average, there is currently enough time scheduled for the round-trip. Also, on most segments, the running time is not highly variable. However, there is not enough time scheduled Westbound and too much time scheduled Eastbound. Indeed, the mean half-cycle time Westbound is 33.7 minutes but the scheduled half-cycle time is 31 min. The scheduled half-cycle time Eastbound is 38 to 39 minutes while the mean half-cycle time is 31.6 minutes.

Operators average an actual layover of only 2.5 minutes at 92 Buf whereas the scheduled layover is 8-9 minutes, while they often hold at 92 Com where Table 3-10 shows an average hold of two minutes. The area around 92 Buf is not a safe and comfortable place to rest and operators prefer to layover at 92 Com where there is a nice business district. We also note that the running time is highly variable on the 92 Buf-92 Com segment in both directions with a segment running time standard deviation of 1.1 minutes on 92 Buf-92 Com and 1.5 minutes on 92 Com – 92 Buf. This is due to the fact that operators do not behave consistently on this segment. It seems that some operators "drag" on this segment to kill time en route rather than hold at 92 Buf. Since there are very few passengers on board in both directions, they can kill time en route without delaying too many passengers and enduring passengers' complaints. The second reason operators kill time en route on 92 Buf-92 Com in both directions and hold at 92 Com segment is to avoid departing early from 92 Com because most boardings Westbound occur on 92 Com-94 Sto. However, by taking very little recovery time at 92 Buf, killing time en route and holding at 92 Com, operators create running time variability.

Only 24% of the buses complete their Westbound trips within the scheduled half-cycle time. Consequently, as shown in Table 3-11, no vehicles are able to depart 95 Red on time for the next trip because so few vehicles can complete the Westbound trip on time and because unreliability has propagated from the previous trips. Since most boardings occur on 95 Red-93 Cot, the reliability is very poor for passengers waiting for the bus on that segment. However, Westbound, without the erratic holds occurring at time points 74% of the buses could finish their westbound trips within the scheduled time, which would improve the reliability for passengers Eastbound. Eastbound, currently, about 90% of the vehicles finish their trips within the scheduled time. However, this does not mean that westbound passengers will benefit from better reliability than Eastbound passengers, since unreliability propagates easily to subsequent trips when there is not enough recovery time at a terminal. Indeed, only 22% of the vehicles depart 92 Buf on time.

Eastbound, without the holds occurring at time points, 99% of the buses could finish their one-way trips within the scheduled time, which would improve reliability for westbound passengers.

3.2.3. Headways

Table 3-12 shows the variability of the headways departing and arriving at each time point. Here again, the ratio between the actual headway and the scheduled headway is used because it eliminates errors which would result if a trip was missing. Indeed if a trip that actually operated from the dataset was missing, the headway would appear greater even if in reality it was not. Using the ratio of actual to scheduled headway avoids this problem.

Westbound	St.Dev (Act Hway/ Sch Hway)	COV (Act Hway/ Sch Hway)	Eastbound	St.Dev (Act Hway/ Sch Hway)	COV (Act Hway/ Sch Hway)
Leaving 92 Buf	0.6	0.58	Leaving 95 Red	0.8	0.81
Arriving 92 Com	0.7	0.61	Arriving 93 Cot	0.8	0.81
Leaving 92 Com	0.6	0.55	Leaving 93 Cot	0.9	0.75
Arriving 94 Sto	0.7	0.65	Arriving 94 Sto	0.9	0.77
Leaving 94 Sto	0.7	0.63	Leaving 94 Sto	0.9	0.77
Arriving 93 Cot	0.7	0.68	Arriving 92 Com	1.0	0.86
Leaving 93 Cot	0.7	0.68	Leaving 92 Com	0.9	0.79
Arriving 95 Red	0.7	0.68	Arriving 92 Buf	0.9	0.75

Table 3-12 Headway variability

As expected, the headways are highly variable due to the variability of the time vehicles spend on each segment of the route. Consequently passengers experience poor reliability. The variability is higher Eastbound because no vehicle is able to depart 95 Red on time. The headways are also very variable leaving the terminals 92 Buf and 95 Red because vehicles are inheriting the unreliability over a day of operation. Headway variability can propagate from one trip to the next if enough recovery time is not scheduled at the end of the trip.

It is generally expected that the variability of the headways increases over a segment and this is true on all segments except on 92 Com-92 Buf where the variability of the headway decreases slightly. Finally, we observe that the variability of the headway decreases between the headway arriving at a time point and the headway departing from the time point. Indeed, the schedule-based holding strategy is supposed to decrease the variability of the time vehicles spend on the segments of the route and, consequently, headway variability.

3.3. Modeling the current situation

The purpose of this section is to confirm that the model is producing results which are consistent with the data if the existing conditions are run on the model. All the assumptions and hypotheses presented in Chapter 2 are employed with the exception of the enforcement of schedule-based holding. The holds occurring at time points on the route are drawn from the hold time distributions computed from the current data. Likewise, the recovery time occurring at terminals are drawn from the recovery time distributions. As in all the model runs, the running time (from the departure at the starting time point to the arrival at the next time point) are drawn from the running time distributions.

The simulation is done from the beginning of the day with the distributions obtained from the AVL data between 16:00 and 17:00. This will probably overstate the headway variability if buses currently pull out from the garage shortly before the PM Peak period.

Such an approach implicitly assumes that the current holding time at time points is not correlated with the running time on the segment. Table 3-13 shows the correlation analysis between the running time on each route segment and the holding time at the second time point of the segment for the set of operators who drove at least five times between 16:00 and 17:00.

Operator ID / Segment	9969	20439	2422	25378	32445	33801	33982	36692
92 Buf-92 Com	-0.23	-0.61	0.14	0.28	0.34	0.75	-0.66	0.15
92 Com-94 Sto	-0.37	0.38	-0.16	0.72	-0.28	0.13	-0.58	-0.33
94 Sto-93 Cot	0.02	0.86	0.28	-0.34	0.04	0.82	-0.40	0.12
95 Red - 93 Cot	0.74		0.53	0.11	0.05		0.78	
93 Cot - 94 Sto	0.56		-0.20	-0.33	-0.27		-0.07	-0.98
94 sto - 92 Com	-0.04		0.21	0.35	0.20		0.47	0.21

Table 3-13 Correlation coefficient R between running time and holding time

We observe that the correlation is not consistently positive or negative. If schedule-based holding is occuring, we would expect a negative correlation since as the segment running time increases, the holding time decreases. Moreover, the correlation between running time and holding time is very strong on some segments for certain operators. However, the correlation is not generally strong for a specific operator on all segments or on one segment for all operators. Rather, some operators are consistent in their behavior within the month-period studied. Consequently, applying the model to the current situation will tend to overstates the variability of the headways since operator specific behavior is not considered.

Table 3-14 shows the variability of the headways departing and arriving at each time point in the model of the current situation.

Westbound	St.Dev (Act Hway/ Sch Hway)	COV (Act Hway/ Sch Hway)	Eastbound	St.Dev (Act Hway/ Sch Hway)	COV (Act Hway/ Sch Hway)
Leaving 92 Buf	0.9	0.90	Leaving 95 Red	0.9	0.89
Arriving 92 Com	0.9	0.91	Arriving 93 Cot	0.9	0.91
Leaving 92 Com	0.9	0.90	Leaving 93 Cot	0.9	0.89
Arriving 94 Sto	0.9	0.94	Arriving 94 Sto	0.9	0.93
Leaving 94 Sto	0.9	0.91	Leaving 94 Sto	0.9	0.89
Arriving 93 Cot	0.9	0.91	Arriving 92 Com	0.9	0.93
Leaving 93 Cot	0.9	0.90	Leaving 92 Com	0.9	0.91
Arriving 95 Red	1.0	0.98	Arriving 92 Buf	1.0	0.95

Table 3-14 Modeling the current situation

Comparing the model results in Table 3-14 with the actual data shown in Table 3-12 shows very similar headway variability Eastbound. The modeled Westbound headways are slightly higher than the actual conditions shown in Table 3-12. This is because the model assumes all vehicles have been in service throughout the day whereas in fact some vehicles pull out from the garage at 92 Buf. This explains why actual service is better than the model results Westbound as well as why actual service is more consistent Westbound than Eastbound.

The analysis in this section confirms that the model produces results which are broadly consistent with the data and that, if anything, the model will tend to overstate the headway variability.

3.4. Current Situation with Schedule-Based Holding

Tables 3-15 and 3-16 present the modeled mean running times and headway variability between 16:00 and 17:00 with the current schedule but with strict enforcement of schedule-based holding. The current schedule between 16:00 and 17:00 is assumed to operate throughout the operating day which will overstate the headway variability if buses pull out from the garage in the middle of the day. However, it could also understate the variability of the headways if interlining is occurring and buses come from routes where reliability is even worse. There are 7 buses operating with a scheduled headway of 10 minutes. The simulation is based on a sample of 392 bus trips.

Westbound	Sch. RT. (min)	% of vehicles which run the segment within the sch RT	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Depart) (min)	COV (Hway) at the starting TP	COV (Hway) at the ending TP
92 Buf -92 Com	2	86%	98%	2.4	0.07	0.18
92 Com – 94 Sto	10	53%	54%	10 .7	0.16	0.29
94 Sto – 93 Cot	8	98%	42%	7.3	0.23	0.27
93 Cot – 95 Red	7	11%	76%	9.1	0.15	0.28
One-way RT	27			29.4		
Layover at 95 Red	4			1.6		
One-way trip	31			31.0		

Table 3-15 Current schedule with on-time departure enforcement (Westbound)

Eastbound	Sch. RT. (min)	% of vehicles which run the segment within the sch RT	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Depart) (min)	COV (Hway) at the starting TP	COV (Hway) at the ending TP
95 Red – 93 Cot	10	92%	74%	9.9	0.14	0.26
93 Cot – 94 Sto	8	53%	82%	9.1	0.11	0.32
94 Sto– 92 Com	9	58%	37%	9.5	0.26	0.33
92 Com– 92 Buf	3	90%	27%	2.3	0.29	0.34
One-way RT	30			30.9		
Layover at 92 Buf	9			7.4		
One-way trip	39			38.3		

Table 3-16 Current schedule with on-time departure enforcement (Eastbound)

It is important to evaluate the current schedule independent of current operator behavior in order to provide a "base" case with schedule-based holding enforced. The second column shows the current scheduled running time between 16:00 and 17:00. The third column computes the percentage of buses which can complete the segments (from the departure at the starting time point to arrival at the ending time point) within the scheduled running time. The third columns in Tables 3-15 and 3-16 are the same as the third columns in Tables 3-10 and 3-11. The fourth column shows the proportion of vehicles which depart the segment starting time point on time. The fifth column presents the mean segment running times, from the time point departure to the arrival at the next time point. Columns 6 and 7 show the coefficient of variation of the headway at the start of the segment and at the end of the segment respectively.

Between 16:00 and 17:00, after a day of operation, approximately 74% of the Westbound trips and 99% of the Eastbound trips are projected to be completed within the allowed time. Consequently, enforcing schedule-based holding allows a larger proportion of vehicles to start their next trip on time. Thus, 98% of the Westbound trips and 74% of the Eastbound trips depart on time. (Since reliability problems propagate to following trips, the percentage of vehicles which depart on time from a terminal is different from the percentage of vehicles which completed the previous trip within the allowed time.)

The mean time vehicles spend on 92 Buf-92 Com, as well as on other segments, is lower than the current mean segment time because unnecessarily long holds are eliminated. On the other hand, on segments such as 93 Cot – 94 Sto, the mean time vehicles spend with the schedule-based holding strategy is longer since vehicles do not leave time points early. Overall, with the schedule-based holding strategy the mean half-cycle time distributions are tighter than currently and the mean half-cycle times are shorter than scheduled. Consequently, the number of vehicles which can depart their subsequent trip on time increases.

In addition to this, with the schedule-based holding strategy, vehicles do not leave terminals early. Thus the mean recovery time at 92 Buf is increased. The fact that vehicles do not leave the time points, or the terminals, erratically directly affects the headways which are less variable than currently. This shows that passengers experience poor reliability on Route 95E primarily due to operator behavior. We also clearly observe in Tables 3-15 and 3-16 the impact of the schedule-based holding strategy being enforced; headway variability decreases significantly between the arrival at a time point and the departure from the time point.

However, we note that the passenger in-vehicle travel time will be slightly longer. Indeed, the mean running time Eastbound is two minutes longer when the schedule-based holding strategy is enforced.

In conclusion, even though the schedule-based holding strategy will lengthen the passenger in-vehicle travel time, it will significantly improve the reliability for the waiting passengers.

In Figures 3-9 through 3-11, the segment running time distributions are shown for each Westbound segment of the route. Also shown on the same figures are both the running time distribution from the departure from the first time point to the arrival at the following time point, as well as the running time distribution from departure from the first time point to that at the following time point. The running time distributions on the 93 Cot-95 Red segment is not shown since vehicles layover at the terminal before starting a new trip.

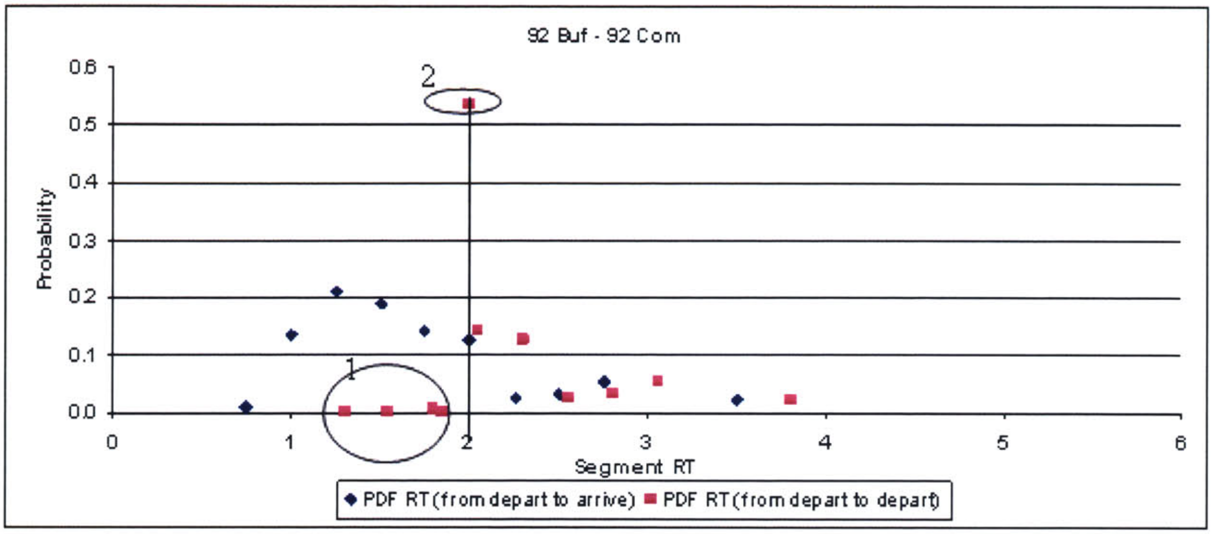


Figure 3-9 Running time distributions on segment 92 Buf-92 Com

Figure 3-9 shows the running time distributions on segment 92 Buf-92 Com. The scheduled segment running time is represented by the line at 2 minutes. The (blue) dots to the left of the scheduled running time represent vehicles which complete the segment within the scheduled running time. The sum of their probabilities is 0.86; i.e., 86% of the vehicles can complete the first segment within the scheduled time. This is as shown in Table 3-15.

The (blue) dots to the right of the scheduled running time represent the vehicles which took longer than the scheduled running time to complete the segment. In this case, 14% of the vehicles could not complete the first segment within two minutes.

The data points in zone 1 represent the vehicles which complete the first segment within two minutes but depart before spending two minutes on the segment. These vehicles are late and need to depart at their scheduled departure time from 92 Com or as soon as they complete handling passengers at 92 Com. We note that the probability of this occurrence is very small: only 0.017.

The data point in zone 2 represents all the vehicles which left 92 Buf on time and run the first segment within two minutes. Consequently, they were held at 92 Com until their scheduled departure time and spent two minutes on the segment. Thus, 54% of vehicles departed both 92 Buf and 92 Com on time. Even though 98% of the vehicles left 92 Buf on time and 86% of the vehicles ran the segment within the scheduled segment running time, the proportion of vehicles able to depart 92 Com on time and also left 92 Buf on time is no higher than 54%. This is because vehicles also need to handle passengers at 92 Com and cannot depart as soon they arrive. Based on the data, we assume a dwell time of 0.3 minutes at each time point of the route.

The (pink) dots to the right of the scheduled running time represents vehicles which either run the segment in more than two minutes or run the segment in just less than two minutes but spent more than two minutes on the segment because of the dwell time of 0.3 minutes at the time point. We note that the (pink) dots are similar to the corresponding (blue) dots but are shifted to the right by the dwell time of 0.3 minutes. The sum of their probabilities is 0.44.

Figure 3-10 shows the running time distributions on the 92 Com-94 Sto segment.

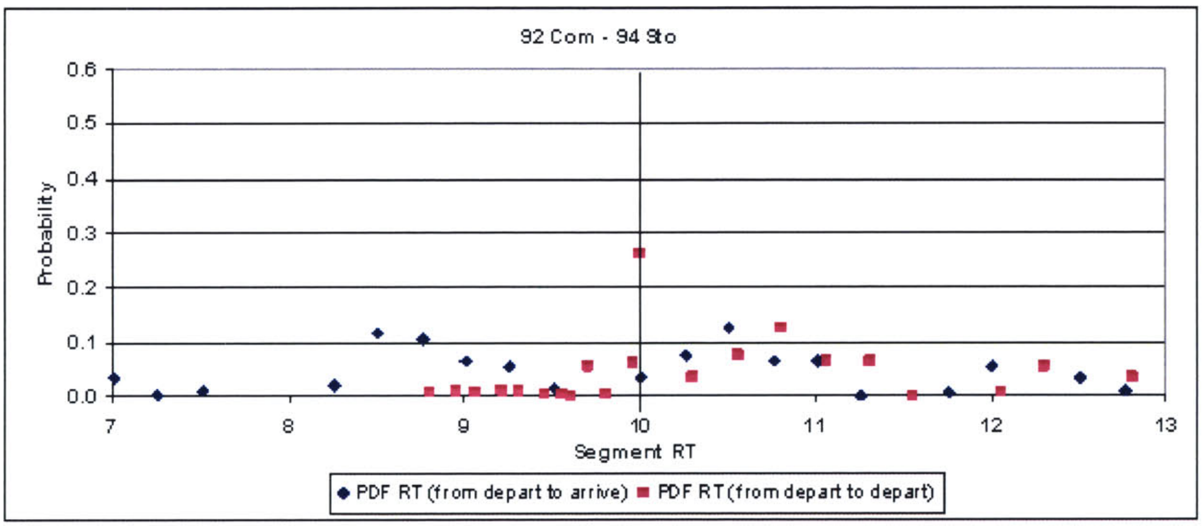


Figure 3-10 Running time distributions on segment 92 Com-94 Sto

The (blue) dots situated to the left of the scheduled running time represent 53% of the vehicles, meaning 53% of vehicles can run the segment within 10 minutes. The 47% of vehicles which cannot run the segment within the scheduled running time are represented by the (blue) dots to the right of the scheduled running time.

According to Table 3-15, 42% of the vehicles depart 94 Sto on time. Figure 3-10 shows that 26% of the vehicles which departed 92 Com on time, run the segment within the scheduled segment running time, spend a total of ten minutes on the segment and depart 94 Sto on time. Further, 16% of vehicles departed 92 Com late but caught up to the schedule by running faster on this segment and also departed 94 Sto on time. This 16% of vehicles are represented by some of the (pink) dots to the left of the scheduled segment running time.

The 58% of vehicles which did not depart 94 Sto on time fall into three categories. First are those vehicles which departed 92 Com late, ran the segment within 10 minutes but could not catch up to the schedule. These vehicles are represented by some of the (pink) dots to the left of the scheduled running time. The second category are those vehicles which departed 92 Com late and either ran the segment in more than 10 minutes or ran the segment in slightly less than 10 minutes but spent more than 10 minutes on the segment in order to handle passengers at 94 Sto. These vehicles are also represented by some of the (pink) dots to the right of the scheduled segment running time. The third category of vehicles departed on time from 92 Com but could not depart on time from 94 Sto because they took too much time to run the segment and handle passengers at 94 Sto. These vehicles are the remaining (pink) dots to the right of the scheduled running time.

Overall, we note that the distribution of the running time from the departure at 92 Buf to the departure at 94 Sto is more spread than that between 92 Buf and 92 Com. This is because fewer vehicles were able to depart 92 Com on time and run the segment within the scheduled running time.

Figure 3-11 shows the running time distributions on 94 Sto-93 Cot segment. The (pink) dots to the left of the scheduled segment running time represent 56% of the vehicles, i.e, the proportion of vehicles which spent less than 8 minutes on the segment. This percentage is large because, as seen before, only 42% of the vehicles were able to depart 94 Sto on time but the scheduled running time on 94 Sto-93 Cot allows 98% of vehicles to run the segment within 8 minutes. Thus, 64% of the vehicles which departed late from 94 Sto (representing 37% of all vehicles) are able to catch up to the schedule thanks to the long scheduled running time. These vehicles are represented by some of the (pink) dots to the left of the scheduled segment running time.

39% of the vehicles departed both 94 Sto and 93 Cot on time. Consequently, 76% of vehicles are able to depart 93 Cot on time. Thus reliability will be improved for passengers waiting on the last segment of the route. Thus 24% of the vehicles cannot depart 93 Cot on time either because they departed too late from 94 Sto and/or they took longer than eight minutes to complete the segment.

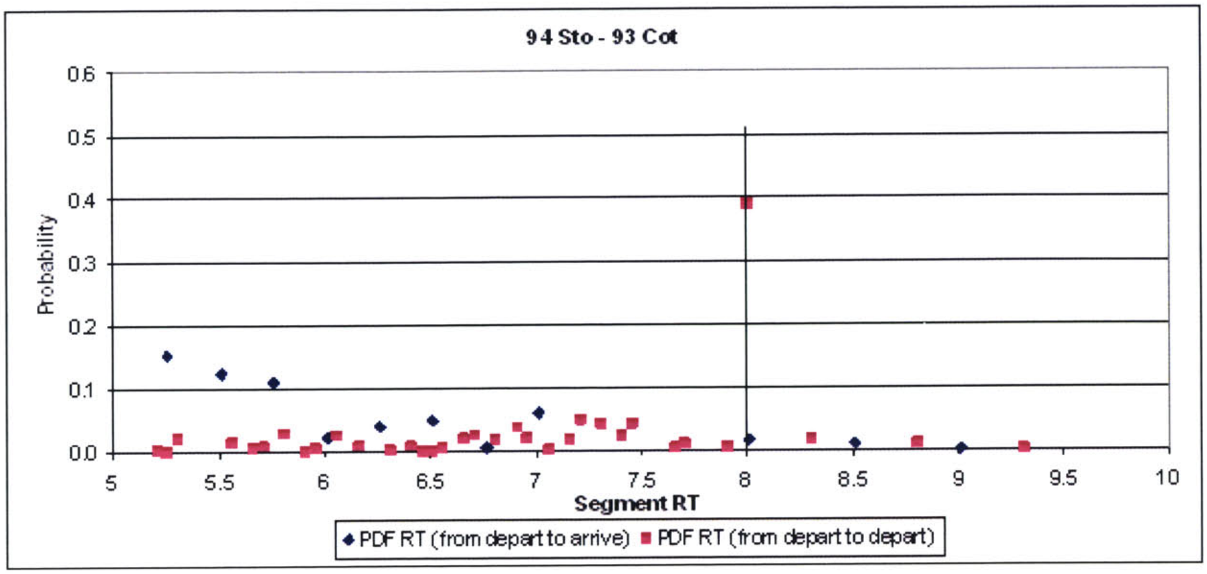


Figure 3-11 Running time distributions on segment 94 Sto-93 Cot

To summarize, this section has shown that enforcing schedule-based holding is critical to improving reliability for the waiting passengers along the route because it significantly lowers the variability of the headways compared to the current situation.

3.5. Traditional Approach

In section 1.4 Current Practice, we reviewed the traditional ways to set vehicle scheduled running times. Transportation Management and Design (TMD), which had been consulted by the CTA in 2003, proposed to set running times at a level where at least 65 percent of trips would have sufficient time to complete their trips on schedule. This section focuses on evaluating the "best" percentile of the running time distribution to implement on each segment of the route, assuming that the same percentile is used for every segment.

The analysis is not limited to finding the cost of the schedule if the 65th percentile is implemented on each segment. Rather the intent is to find the percentile to implement on each segment in order to minimize the cost for the passengers while maintaining a reliable service. Figure 3-12 shows the cost to passengers and to the CTA of implementing a wide range of percentiles. The x axis shows the selected percentile and the y axis shows the hourly costs. The layover time, and consequently the on-time departure probability from each terminal, is a function of the number of buses, headway and percentile selected. Thus, the recovery time is not always set at a certain value but varies. However, the assumption is made that recovery time will always allow at least 90% of the vehicles to run each trip within the scheduled half cycle time.

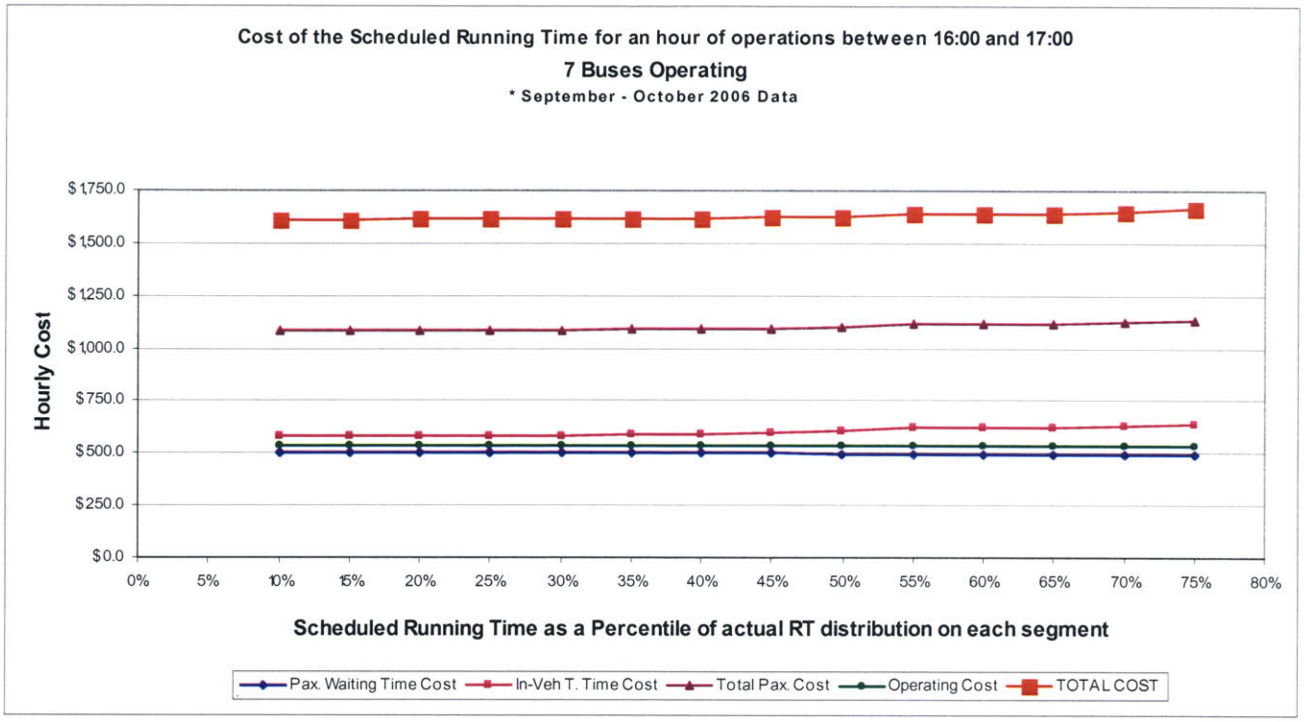


Figure 3-12 Cost as a function of running time percentile

For this example, it should be noted that the waiting time cost decreases slightly and the in-vehicle travel time cost increases slightly with increasing percentile of the running time selected. However, the total passenger cost does not vary significantly across the full range of solutions. The minimum passenger cost solution is at the 10th percentile of running times, however, there is only a 5% difference in total passenger cost when varying the running times from the 75th percentile to the 10th percentile on each segment of the route. Implementing the 50th percentile on each route segment costs only 1.5% more in total passenger cost than the 10th percentile while yielding a more reliable service. Moreover, in reality, implementing the 10th percentile on each segment of the route would essentially mean eliminating all time points on the route. Seven buses are needed to implement any schedule between the 10th and 75th percentile of the running time distribution. Consequently, the operating cost does not vary and stays constant for all running time distribution percentiles on this route.

Consequently, if CTA chose to implement the same percentile on each segment of the route, one logical alternative would be to use the 50th percentile solution which is presented in section 3.5.1. The 65th percentile solution, which is the method recommended by TMD, is examined in section 3.5.2.

3.5.1. 50^{th} percentile solution

Tables 3-17 and 3-18 present the 50^{th} percentile solution. The scheduled running times are rounded up to the next integer because most operators schedule to the minute. The schedule presented in Tables 3-17 and 3-18 is assumed to be implemented throughout the operating day and analyzed between 16:00 and 17:00. There are 7 buses operating with a scheduled headway of 10 minutes and the simulation includes a sample of 392 bus trips. The percentage of vehicles which can complete the segment within the scheduled running time is presented in the third column of the table. The tables also show the percentage of vehicles starting each segment on time and the coefficient of variation at the start and end of each segment. The scheduled layover is obtained as explained in chapter 2; to ensure that 90% of the trips can be completed within the allowed time. Consequently, more recovery time is given at 92 Buf because the Eastbound segment running time distributions are wider than the Westbound segment running time distributions.

Setting the segment scheduled running times at a level where (at least) 50% of the vehicles would have sufficient time to run the segment allows 97% of the trips in both directions to be completed within the allowed time. Consequently, implementing the 50^{th} percentile schedule allows a larger proportion of vehicles to start their next trip and each segment on time. Indeed, 95% of the Westbound trips and 97% of the Eastbound trips depart on time. We note that the recovery time allocation allows more vehicles to start their Eastbound trip on time than their Westbound trip. This is important since the Eastbound direction is the heavier demand direction in this time period.

When the 50^{th} percentile solution is implemented, the mean one-way running times are longer than the scheduled ones. However, the trips in both directions can be achieved within the allowed time. The scheduled half-cycle time is increased by three minutes Westbound, resulting in a better balance between the two directions.

Compared to the current schedule with schedule-based holding, the 50^{th} percentile solution provides shorter passenger in-vehicle time since shorter holds occur at time points because less running time is scheduled. The 50^{th} percentile solution has a mean one-way running times one minute shorter Westbound and 1.5 minutes shorter Eastbound than for the current schedule with schedule-based holding.

It should be noted that the headways are slightly more variable with the 50th percentile approach compared to the current schedule with schedule-based holding. We again observe that the headways departing time points are less variable than the headways arriving at time points.

In conclusion, the 50th percentile solution shows a similar level of reliability for the waiting passengers as the current schedule with schedule-based holding but shortens the in-vehicle travel times.

Wesbound	Sch. RT. (min)	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Depart) (min)	COV (Hway) at the starting TP	COV (Hway) at the ending TP
92 Buf – 92 Com	2	95%	2.4	0.09	0.20
92 Com – 94 Sto	10	53%	10.7	0.18	0.30
94 Sto – 93 Cot	6	42%	6.1	0.24	0.28
93 Cot – 95 Red	9	38%	9.1	0.25	0.33
One-way RT	27		28.2		
Layover at 95 Red	7		5.4		
One-way trip	34		33.6		

Table 3-17 50th percentile running time solution (Westbound)

Eastbound	Sch. RT. (min)	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Depart) (min)	COV (Hway) at the starting TP	COV (Hway) at the ending TP
95 Red – 93 Cot	8	97%	8.6	0.05	0.23
93 Cot – 94 Sto	8	53%	9.1	0.15	0.33
94 Sto– 92 Com	9	33%	9.5	0.28	0.34
92 Com– 92 Buf	3	24%	2.3	0.30	0.36
One-way RT	28		29.5		
Layover at 92 Buf	8		6.2		
One-way trip	36		35.7		

Table 3-18 50th percentile running time solution (Eastbound)

3.5.2. 65th percentile solution

Tables 3-19 and 3-20 show the equivalent result for the 65th percentile solution. This schedule is examined because it was the method recommended by TMD.

Wesbound	Sch. RT. (min)	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Depart) (min)	COV (Hway) at the starting TP	COV (Hway) at the ending TP
92 Buf – 92 Com	2	94%	2.4	0.11	0.20
92 Com – 94 Sto	11	52%	11.2	0.18	0.30
94 Sto – 93 Cot	6	60%	6.2	0.20	0.25
93 Cot – 95 Red	10	48%	9.1	0.21	0.31
One-way RT	29		28.8		
Layover at 95 Red	5		4.8		
One-way trip	34		33.6		

Table 3-19 65th percentile running time solution (Westbound)

Eastbound	Sch. RT. (min)	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Depart) (min)	COV (Hway) at the starting TP	COV (Hway) at the ending TP
95 Red – 93 Cot	8	97%	8.6	0.05	0.23
93 Cot – 94 Sto	9	53%	9.5	0.15	0.33
94 Sto– 92 Com	10	48%	9.9	0.24	0.31
92 Com– 92 Buf	3	50%	2.3	0.22	0.30
One-way RT	30		30.4		
Layover at 92 Buf	6		5.3		
One-way trip	36		35.7		

Table 3-20 65th percentile running time solution (Eastbound)

Setting the segment scheduled running times at a level where (at least) 65% of the vehicles would have sufficient time to run the segment allows 97% of the Westbound trips and 96% of the Eastbound trips to be completed within the allowed time. 94% of the Westbound trips and 97% of the Eastbound trips depart on time.

By implementing the 65th percentile on each segment of the route, the in-vehicle travel time is longer than in the 50th percentile schedule. Indeed, we observe longer scheduled running times and consequently longer mean running times on each direction. Here again, the schedule-based holding strategy shows a significant beneficial impact by decreasing the headway variability at each time point. The headway variability for the 65th percentile schedule is similar to that for the 50th percentile schedule.

In conclusion, compared to the 50th percentile schedule, the 65th percentile schedule shows a similar level of reliability for waiting passengers but lengthens the total running time by almost 2 minutes.

3.6. Generalized cost minimization approach

Tables 3-21 and 3-22 present the schedule obtained applying the proposed generalized cost minimization process. The schedule presented below minimizes the total weighted customer minutes which is given by the sum of the passenger waiting minutes (weighted by 1.5) and the passenger in-vehicle minutes (see chapter 2 for a discussion of this approach).

Wesbound	Sch. RT. (min)	% of vehicles which run the segment within the sch RT	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Depart) (min)	COV (Hway) at the starting TP	COV (Hway) at the ending TP
92 Buf – 92 Com	2	86%	97%	2.4	0.09	0.19
92 Com – 94 Sto	9	42%	54%	10.4	0.18	0.30
94 Sto – 93 Cot	5	43%	17%	5.8	0.27	0.31
93 Cot – 95 Red	9	60%	4%	9.1	0.30	0.38
One-way RT	25			27.7		
Layover at 95 Red	9			6.0		
One-way trip	34			33.7		

Table 3-21 Generalized cost minimization solution (Westbound)

Eastbound	Sch. RT. (min)	% of vehicles which run the segment within the sch RT	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Depart) (min)	COV (Hway) at the starting TP	COV (Hway) at the ending TP
95 Red – 93 Cot	6	17%	97%	8.0	0.05	0.23
93 Cot – 94 Sto	6	15%	5%	8.7	0.22	0.37
94 Sto– 92 Com	8	31%	1%	9.2	0.36	0.42
92 Com– 92 Buf	2	49%	1%	2.3	0.41	0.46
One-way RT	22			28.3		
Layover at 92 Buf	14			7.4		
One-way trip	36			35.7		

Table 3-22 Generalized cost minimization solution (Eastbound)

Implementing the schedule shown in the above tables would allow 97% of the trips in both directions to be completed within the allowed time and 97% of the trips in both directions would be able to depart on time.

However, the scheduled segment running times obtained with the generalized cost minimization approach are not reasonable for the operators; the approach is the same as suppressing each time point except 92 Com. Indeed, we note that a very small proportion of vehicles are able to depart the segments on time, especially Eastbound. The schedule has been developed this way because on most segments of this route, more passengers are onboard than waiting for service, except at 92 Com. Consequently, the generalized cost minimization approach sets low percentiles on the segments where there are more through passengers than waiting for service in order not to disadvantage a significant number of through passengers by holding at time points. For this reason, the only segment where a longer running time is proposed with the generalized cost minimization approach is 92 Buf-92 Com in order to allow a larger proportion of vehicles to be on time at 92 Com. Since there are few through passengers at 92 Com compared to the number of passengers waiting on the next segment, holds at 92 Com will benefit many waiting passengers and disadvantage few through passengers.

These results are consistent with the results of other research such as that of Liu [18]. He found that "time points should be located at places where the number of boarding passengers is well predominant (sic) over the number of through passengers". Further, he adds that "if such place (sic) is chosen to be a time point, then the higher the ratio of the boarding passengers to the number of through passengers, the greater the amount of slack time". Slack time in Liu's research is the equivalent of holding time in this research.

Even though the ratio of the number of waiting passengers to the number of through passengers is less than 1 at 93 Sto (Westbound) and at 93 Cot (Westbound), the scheduled running times on 92 Com-94 Sto and 94 Sto-93 Cot allow 42% and 43% of the vehicles to complete their segments within the scheduled times. The proportion of vehicles which are able to complete the segment within the scheduled time seems large but it is only because the distribution of running times on these segments is tight. In order to minimize the total weighted passenger cost, we recommend implementing the 10th percentile on 92 Com-94 Sto and the 5th percentile on 94 Sto-93 Cot which give segment running times of 8.27 minutes and 4.01 minutes respectively. When the segment running times are rounded up to the next integer, the segment scheduled running times correspond to the 42nd and 43rd percentiles of the respective running time distributions on their respective segment distributions. Even with the 42nd and 43rd percentiles, less holding occurs than in the current situation on these segments. The mean times vehicles spend on these segments are lower than with the current schedule since there is less time scheduled. One minute less is allocated to the 92 Com – 94 Sto segment, and three minutes less to the 94 Sto – 93 Cot segment. The running times scheduled on these segments are also shorter than for the 50th percentile schedule.

Eastbound, the scheduled segment running times on the three first segments, 95 Red – 93 Cot, 93 Cot – 94 Sto and 94 Sto – 92 Com, are set at level where 17%, 15% and 31% of the vehicles have sufficient time to complete the segments within schedule. On these first three segments, it is important that the vehicles run as quickly as possible since most of the boardings occur on the first segment which includes the Red Line terminal while on the following segments there are less passengers waiting than through passengers. Even though the number of waiting passengers on 92 Com-92 Buf is small compared to the number of through passengers, we recommend implementing the 31st percentile on 94 Sto-92 Com. This is due to the fact that the running time to schedule on this segment can be "large" without disadvantaging through passengers. The vehicles are so late that they will arrive at time point 92 Com later than their scheduled departure time and consequently will almost never hold. We observe that only 1% of the vehicles depart 92 Com on time. The running times scheduled on these three first Eastbound segments are shorter than the running times for the 50th percentile schedule.

The percentile on the last segment in each direction on any bus route can range from the 0th percentile to the 100th percentile since operators begin their layover as soon as they arrive at the terminal. The scheduled segment running times can be changed on these segments without any consequences for reliability or passenger service quality on the route as long as operators are instructed not to kill time en route.

The generalized cost minimization approach proposes a schedule with shorter scheduled running times than the 50th percentile schedule on each segment of the route. Since fewer holds are implemented, the mean one-way running times are slightly shorter than the mean one-way running times obtained with the 50th percentile approach.

However, as expected, the headways with the schedule obtained using the generalized cost minimization approach are more variable than the headways with the 50th percentile approach. We also observe that the variability of the headways does not decrease significantly between arrivals and departures at a time point because so few vehicles are affected by holding. As noted previously, the schedule proposed under the generalized cost minimization approach is equivalent to eliminating all time points on the route except 92 Buf.

In conclusion, the schedule obtained with the generalized cost minimization approach will probably provide shorter in-vehicle travel time for onboard passengers but not as good reliability for the waiting passengers compared to the 50th percentile approach.

3.7. Cost Comparison

Table 3-23 shows the costs for the passengers and for the CTA in dollars and in minutes for each schedule presented in the previous sections. The costs are calculated as explained in Chapter 2 with the following cost parameters:

Waiting time cost per passenger hour= $12/passenger-hour
In-vehicle travel time cost per passenger hour= $8/passenger-hour
Operating cost per hour of operation=$76/passenger-hour[10](excluding pension costs)

The fourth section of the table shows the excess waiting time, in-vehicle travel time and total time. The excess waiting time is that portion of the waiting time cost which is directly related to the variability of the headways on the route. If the route is perfectly reliable (i.e. the headways equal those scheduled), the excess waiting time will be equal to 0. The excess in-vehicle travel time is the time spent onboard by the though passengers when the vehicles are holding. The excess waiting and in-vehicle times presented in Table 3-23 are weighted by the number of passengers affected.

The third and fifth sections of the table show the difference between each solution and the current situation for passenger minutes and excess passenger minutes, respectively, in percentage terms, a positive value indicating a lower cost for the alternative solution.

[10] *Source: 2007 CTA Budget Recommendation p.139: Revenue Hours/Operating Cost= $76/hr of operation*

	Current situation	Current schedule with sch. Based holding	Traditional Approach (50%)	Traditional Approach (65%)	Generalized cost minimization approach
Pax Waiting Time Cost	$572	$506	$506	$504	$511
In-veh TT cost	$566	$613	$577	$590	$557
Operating Cost	$532	$532	$532	$532	$532
TOTAL COST	**$1,670**	**$1,651**	**$1,615**	**$1,626**	**$1,600**
Waiting time in pax-min	2861	2530	2528	2519	2553
In vehicle TT in pax-min	4244	4599	4327	4423	4179
TOTAL PAX-MIN	**7105**	**7130**	**6855**	**6942**	**6732**
TOTAL WEIGHTED PAX-MIN	**8535**	**8394**	**8119**	**8202**	**8009**
% difference in waiting time		12%	12%	12%	11%
% difference in in-vehicle TT		-8%	-2%	-4%	2%
% difference in pax-min		**0%**	**4%**	**2%**	**5%**
% difference in weighted pax-min		**2%**	**5%**	**4%**	**6%**
Excess waiting time in pax-min	967	117	116	106	140
Excess in-vehicle time in pax-min	344	572	299	396	151
Excess total time	**1311**	**688**	**415**	**502**	**291**
Excess total weighted time	**1795**	**747**	**473**	**555**	**361**
% difference in excess waiting time		88%	88%	89%	85%
% difference in excess in-vehicle TT		-66%	13%	-15%	56%
% difference in excess pax-min		**48%**	**68%**	**62%**	**78%**
% difference in excess weighted pax-min		**58%**	**74%**	**69%**	**80%**

Table 3-23 Cost Comparison

First, we observe that the current schedule with schedule-based holding significantly improves reliability for the waiting passengers compared to the current situation. Indeed, when the schedule-based holding strategy is enforced, the total passenger waiting time is reduced by 12% compared to the current situation and the excess passenger waiting time is reduced by 88%. This further supports the view that passengers experience long waiting times on Route 95E primarily as a result of operator behavior. The result is headway variability since operators are not behaving consistently at time points. As the variability of the headway increases, the route becomes less reliable.

We observe that any of the alternatives considered substantially improves reliability for waiting passengers on route 95E compared to the current situation. The passenger waiting times for each solution are much smaller than for the current schedule. In the 65th percentile approach and the current schedule with schedule-based holding enforcement, the through passengers are disadvantaged compared with the current situation. Through passengers are disadvantaged to the greatest extent with the current schedule and schedule-based holding enforced. Indeed, too much running time is scheduled currently.

The schedules obtained with the generalized cost minimization approach as well as the 50^{th} percentile schedule have the lowest overall and weighted passenger costs. However, the excess time experienced by passengers with the two approaches is very different. Indeed, even though, the 50^{th} percentile solution saves about half an hour (or 21%) of excess passenger waiting time compared to the generalized cost minimization approach, it lengthens the through passengers in-vehicle time by over two hours or 50%. Overall, the generalized cost minimization schedule saves a total of 112 (or 24%) of excess weighted passenger minutes compared with the 50^{th} percentile schedule. In summary, the generalized cost minimization schedule clearly shows more benefit for passengers compared to the 50th percentile scheduling approach and, in particular, for through passengers. Compared to the current situation, the generalized cost minimization schedule saves 80% of excess total weighted time.

Adding an extra bus to the route while keeping the same scheduled headway would sharply increase the operating cost and would not show any significant improvement in reliability. Indeed, almost all vehicles are able to depart their next trip on time with the implementation of the generalized cost minimization schedule.

Consequently, if CTA were to reschedule Route 95E, between 16:00 and 17:00, we would advise the implementation of the generalized cost minimization schedule with the current number of buses in order to improve the passenger service quality. However, this will only be true if schedule-based holding is enforced. We have shown that without strict enforcement of schedule-based holding, the headways become more variable which triggers unreliability and passengers experience longer in-vehicle travel time because operators do not leave time points consistently.

The next chapter is a sensitivity analysis which will investigate the conditions under which the generalized cost minimization approach offers the most benefits over the traditional approach.

Chapter 4. Sensitivity Analysis

This chapter investigates the potential benefits of the generalized cost minimization approach to schedule design. The sensitivity analysis performed here seeks to identify conditions under which the generalized cost minimization scheduling process shows the most benefits over the traditional scheduling process.

Specifically, this chapter explores the sensitivity of the scheduling method to:

- The number of boarding passengers (section 4.2)
- The ratio of the waiting passengers to through passengers on that segment (section 4.3)
- The location of the segment on the route (section 4.4)
- The ratio of waiting passengers on later segments to through passengers (section 4.5)
- The length of the route (section 4.6)

While sections 4.2 through 4.6 investigate the benefits of the generalized cost minimization approach on routes with simple demand patterns, section 4.7 considers more realistic demand patterns.

4.1. Route description

The analyses in this chapter are conducted on a loop route. The basic loop route has four segments with a terminal A(E) and time points at B, C, D. Four buses operate on this route with a headway of eight minutes. The segment running time distributions used on this route are those of Route 95E. In sections 4.6 and 4.7.2, an extended version of the loop route with eight segments is analyzed with terminal A(I) and time points at B, C, D, E, F, G and H. On this longer route, there are 7 buses running with a headway of nine minutes. The segment running time distributions used on this route are those of Route 95E in both directions.

In all of the sensitivity analyses in this chapter, the hypotheses and assumptions outlined in previous chapter are used. The analysis hour is 16:00 and 17:00 and boardings and alightings occur only at time points. It is reasonable to believe that these assumptions will not adversely impact the results since we are assuming that a schedule-based holding strategy is enforced.

4.2. Number of boardings

This section investigates the impact of the number of boardings on the benefits of the proposed scheduled method. Table 4-1 shows two scenarios with the same ridership pattern, but with 50% more boardings in the second scenario. In each scenario, one quarter of the boardings occur at the terminal and three quarters at the third time point on the route. All passengers alight at time point D.

The first section of the table shows the number of boardings per trip occurring at each time point. The second section shows the expected load per trip departing each time point. The third section shows the scheduled running time, which minimizes the total passenger weighted cost with the 50^{th} percentile schedule indicated in parenthesis. The sixth section gives the percentage of vehicles which can complete each segment within the scheduled time. The seventh and eighth sections show the percentage of trips which can be completed within the allowed time and percentage of trips which can depart A(E) on time during the period. The ninth section shows the difference in passenger minutes between the schedule obtained with the generalized cost minimization approach and the 50^{th} percentile solution. Finally, section ten shows the difference between these solutions in percentage terms, a positive value indicating a lower cost for the generalized cost minimization approach.

Notation used in Table 4-1 and in all scenario tables in this chapter include:

- **nb (A)** = average passenger boardings per trip at time point A
- **Exp Load / trip (A)**= expected load per trip departing time point A
- **Sch RT (A-B)** = scheduled running time on segment A-B
- **Percentile (A-B)** = percentile of the running time distribution on segment A-B

We note that the schedule which minimizes the total passenger cost is the same in both cases independent of the passenger volume. The running time on the first segment of the route is set at a level where only 17% of the buses have sufficient time in order not to disadvantage the through passengers, since there are no passengers waiting at time point B. However, the scheduled running time on the second segment is set so that 87% of the buses have sufficient time in order to maintain good reliability for the passengers waiting at time point C, since, there are more passengers waiting at C than on the vehicles. Naturally, a very low percentile is selected on the third segment, segment C-D, since no boardings occur on this portion of the route. The scheduled running time on the last segment of any bus route can vary without any negative consequence on the onboard passengers or waiting passengers as long as operators do not kill time en route. We have set it at the 60th percentile here.

Scenario	I	II
nb (A)	8	12
nb(B)	0	0
nb(C)	24	36
nb(D)	0	0
Exp Load / trip (A)	8	12
Exp Load / trip (B)	8	12
Exp Load / trip (C)	32	48
Exp Load / trip (D)	0	0
Sch RT (A - B) (2min)	1	1
Sch RT (B - C) (10min)	11	11
Sch RT (C - D) (6min)	4	4
Sch RT (D - E) (9min)	9	9
Total Sch RT before layover (27min)	25	25
Sch. Layover in min at E (5min)	7	7
Percentile (A-B) (86%)	17%	17%
Percentile (B-C) (53%)	87%	87%
Percentile (C-D) (82%)	15%	15%
Percentile (D-E) (60%)	60%	60%
Percentage of vehicles which can run the trip within the allowed time (92%)	92%	92%
Average percentage of vehicles which depart A on time (91%)	91%	91%
Diff. in waiting time pax-min	2	2
Difference in-vehicle TT pax-min	6	6
Difference in total pax-min	8	8
Difference in weighted pax-min	9	9
% Diff. in waiting time pax-min	0%	0%
% Diff. in-vehicle TT pax-min	0%	0%
% Difference in total pax-min	0%	0%
% Difference in weighted pax-min	0%	0%

Table 4-1 Impact of total boardings

The demand patterns in these two scenarios are fairly extreme, however, they show that the running times scheduled on the segments of a route are not sensitive to the total number of boardings on a route although they may be more sensitive to the ratio of waiting passengers to through passengers.

We observe that for both scenarios, the schedule obtained with the generalized cost minimization approach shows small benefits in total cost over the 50th percentile schedule. In fact, both schedules have the same cost for the waiting passengers because both schedules introduce enough holds either at time point B or C to maintain good reliability for passengers waiting at C.

Both schedules have the same cost for the onboard passengers because the sum of the running time scheduled on the two first segments is identical. Any hold at D would not disadvantage onboard passengers because they get off as soon as the vehicles arrive at the time point.

In conclusion, the generalized cost minimization schedule is not sensitive to the number of boardings and showed small benefits over the 50^{th} percentile schedule in scenarios I or II.

4.3. Ratio of waiting passengers to through passengers

As seen previously, the generalized cost minimization schedule is sensitive to the ratio of waiting passengers to through passengers. It is expected that as the ratio increases on a segment, more scheduled time is given on the preceding segment to improve reliability for the waiting passengers, i.e. to decrease the variability of the headway departing the starting time point. Similarly as this ratio decreases, less scheduled time will be given on the preceding segment so as not to disadvantage the through passengers.

Table 4-2 investigates how large the ratio of waiting passengers to through passengers needs to be for the generalized cost minimization approach to show significant benefits over the 50^{th} percentile schedule.

Three demand scenarios are presented in Table 4-2 where the ratio of waiting passengers to through passengers at time point C varies from 1 to 5.

We note that the scheduled running time remains the same on the first segment of the route giving only 17% of the vehicles sufficient time because there are no waiting passengers at time point B. We also observe that as the ratio of waiting to through passengers increases, the scheduled running time on the second segment increases in order to improve the reliability for the growing number of passengers waiting at C. This confirms that the scheduled running time is indeed sensitive to the ratio of waiting to through passengers.

Clearly, as the ratio of waiting passengers to through passengers increases, the generalized cost minimization schedule shows greater benefits for waiting passengers compared the 50^{th} percentile schedule. In effect, more than 50% of the vehicles need to be held when the ratio becomes significant in order to improve reliability for the waiting passengers. The opposite phenomenon is observed with passenger in-vehicle time. As the ratio increases, the 50^{th} percentile schedule saves in-vehicle time while the generalized cost minimization schedule requires longer holds to benefit waiting passengers.

To summarize, the proposed schedule in scenario V will probably show significant benefit in excess waiting time. Since section 3.7 showed that small percentage differences in total time lead to significant decreases in excess time. The proposed schedule in scenario III will show less benefit in excess in-vehicle time over the 50th percentile schedule.

Scenario	III	IV	V
nb (A)	8	8	6
nb(B)	0	0	0
nb(C)	8	24	30
nb(D)	0	0	0
Exp Load / trip (A)	8	8	6
Exp Load / trip (B)	8	8	6
Exp Load / trip (C)	16	32	36
Exp Load / trip (D)	0	0	0
Sch RT (A - B) (2min)	1	1	1
Sch RT (B - C) (10min)	10	11	12
Sch RT (C - D) (6min)	4	4	4
Sch RT (D - E) (9min)	9	9	9
Total Sch RT before layover (27min)	24	25	26
Sch. Layover in min at E (5min)	8	7	6
Percentile (A-B) (86%)	17%	17%	17%
Percentile (B-C) (53%)	53%	87%	93%
Percentile (C-D) (82%)	15%	15%	15%
Percentile (D-E) (60%)	60%	60%	60%
Percentage of vehicles which can run the trip within the allowed time (92%)	93%	92%	91%
Average percentage of vehicles which depart A on time (91%)	92%	91%	89%
Diff. in waiting time pax-min	-6	2	26
Difference in-vehicle TT pax-min	27	6	-19
Difference in total pax-min	21	8	7
Difference in weighted pax-min	18	9	20
% Diff. in waiting time pax-min	-1%	0%	2%
% Diff. in-vehicle TT pax-min	2%	0%	-1%
% Difference in total pax-min	1%	0%	0%
% Difference in weighted pax-min	1%	0%	1%

Table 4-2 Ratios of waiting passengers to through passengers

4.4. Location of the segment on the route

This section investigates whether the benefit of the generalized cost minimization approach depends on the location of the segment at which a high ratio of waiting passengers to through passengers occurs. Without holding at time points, the headway variability increases from the terminal to subsequent time points on the route. Table 4-3 shows two scenarios with the ratio of waiting passengers to through passengers equal to 5 on one segment of the route in each case.

Scenario	VI	VII
nb (A)	6	6
nb(B)	30	0
nb(C)	0	30
nb(D)	0	0
Exp Load / trip (A)	6	6
Exp Load / trip (B)	36	6
Exp Load / trip (C)	36	36
Exp Load / trip (D)	0	0
Sch RT (A - B) (2)	2	1
Sch RT (B - C) (10)	7	12
Sch RT (C - D) (6)	4	4
Sch RT (D - E) (9)	9	9
Total Sch RT before layover (27)	22	26
Sch. Layover in min at E (5)	10	6
Percentile (A-B) (86%)	86%	17%
Percentile (B-C) (53%)	15%	93%
Percentile (C-D) (82%)	15%	15%
Percentile (D-E) (60%)	60%	60%
Percentage of vehicles which can run the trip within the allowed time (92%)	93%	91%
Percentage of vehicles which depart A on time (91%)	92%	89%
Diff. in waiting time pax-min	0	26
Difference in-vehicle TT pax-min	119	-19
Difference in total pax-min	119	7
Difference in weighted pax-min	119	20
% Diff. in waiting time pax-min	0%	2%
% Diff. in-vehicle TT pax-min	3%	-1%
% Difference in total pax-min	2%	0%
% Difference in weighted pax-min	2%	1%

Table 4-3 Effect of the segment location

In scenario VI, the number of waiting passengers is five times the number of through passengers at the second time point on the route. Some holding is necessary at the first time point even though reliability is quite high at that time point since it is close to the terminal. The "optimized" scheduled segment running time on the first segment is equal to the 50th percentile solution and no holding is necessary elsewhere since there are no boarding passengers.

In scenario VII, the number of waiting passengers is five times the number of through passengers at time point C. Holding will be necessary only at time point C where passengers board.

From these scenarios, it is clear that the schedule is sensitive to the segment location on the route. The total passenger cost minimizing schedule shows the most overall benefits in scenario VI since in this case no holding after time point B is necessary in order to maintain good reliability for the waiting passengers. Implementing the 50th percentile in this case disadvantages the through passengers without benefiting waiting passengers. In scenario VII, the generalized cost minimization schedule saves passengers more waiting time than the 50th percentile schedule since it introduces long holds at time point C where passengers board; however, this disadvantages onboard passengers.

4.5. Ratio of waiting passengers on later segments to through passengers

Following the previous investigations, we seek to investigate whether the generalized cost minimization approach will show benefits when the total number of waiting passengers on later segments is larger than the number of through passengers at the time point. Holding vehicles at a time point will presumably benefit not only the waiting passengers at that time point but also at the following time points. Table 4-4 shows several scenarios where the ratio of the waiting passengers on later segments to through passengers is greater than one.

In each scenario, the downstream ratio is equal to nine at time point C, and at time point D is equal to zero in scenario VIII, to one in scenario IX, and to four in scenario X.

In all three scenarios, the running time scheduled for the first segment allows 98% of the vehicles to complete the segment within the allowed time because there are no through passengers at B. Indeed, it is more beneficial for the waiting passengers on the route to hold the vehicles at B than to allocate the extra minutes to recovery time at A because doing so decreases the variability of the headways at B. On the second route segment, the scheduled running time is sensitive to the waiting passengers both on the next segment and later segments.

Scenario	VIII	IX	X
nb (A)	0	0	0
nb(B)	2	2	2
nb(C)	18	8	2
nb(D)	0	10	16
Exp Load / trip (A)	0	0	0
Exp Load / trip (B)	2	2	2
Exp Load / trip (C)	20	10	4
Exp Load / trip (D)	20	20	20
Ratio downstream (B)	0	0	0
Ratio downstream (C)	9	9	9
Ratio downstream (D)	0	1	4
Sch RT (A - B) (2)	4	4	4
Sch RT (B - C) (10)	12	11	11
Sch RT (C - D) (6)	4	4	6
Sch RT (D - E) (9)	9	9	9
Total Sch RT before layover (27)	29	28	30
Sch. Layover in min at E (5)	3	4	2
Percentile (A-B) (86%)	98%	98%	98%
Percentile (B-C) (53%)	93%	87%	87%
Percentile (C-D) (82%)	15%	15%	82%
Percentile (D-E) (60%)	60%	60%	60%
Percentage of vehicles which can run the trip within the allowed time (92%)	72%	78%	74%
Percentage of vehicles which depart A on time (91%)	62%	73%	68%
Diff. in waiting time pax-min	33	18	25
Difference in-vehicle TT pax-min	18	10	-13
Difference in total pax-min	52	28	12
Difference in weighted pax-min	69	37	25
% Diff. in waiting time pax-min	5%	3%	4%
% Diff. in-vehicle TT pax-min	1%	1%	-1%
% Difference in total pax-min	2%	1%	1%
% Difference in weighted pax-min	3%	2%	1%

Table 4-4 Effect of waiting passengers on later segments to through passengers

We note that the schedule is sensitive to the ratio of waiting passengers on later segments to through passengers. Indeed, the scheduled running times on segment B-C in scenarios IX and X are the same even though there are four times more waiting passengers at C in scenario IX than in scenario X. This is due to the fact that there are 16 passengers in scenario X waiting downstream at time point D who will benefit from the holds at time point C.

We observe that the schedule is also sensitive to the ratio of waiting passengers on the next segment to through passengers since the running time scheduled on segment B-C in scenario VIII is larger than in scenarios IX and X because there are significantly more passengers waiting at C in scenario VIII.

We note that there are more vehicles which are able to complete their trips within the allowed time in scenario X than in scenario VIII even though more running time is scheduled in scenario X than in scenario VIII. Holding vehicles at D longer (as in scenario X) delays them less than holding them at C longer (as in scenario VIII) because it results in a larger proportion of vehicles arriving late at D and consequently shorter holds at that time point. On the other hand, a larger proportion of vehicles are arriving early at C and the holds at this time point will be longer because this time point is closer to the starting terminal.

In conclusion, the schedule is sensitive to the downstream ratio but also to the ratio of waiting passengers on the following segment to through passengers at the time point where the hold occurs. In each scenario, the generalized cost minimization schedule shows significant benefits for the waiting and onboard passengers over the 50th percentile schedule.

4.6. Route Length

It has been shown that for short routes, the generalized cost minimization schedule is clearly sensitive to the number of waiting and through passengers and showed in most scenarios significant benefits over the 50th percentile approach. This section investigates whether the generalized cost minimization approach shows more benefits on a longer route where recovery occurs less frequently. Three demand scenarios are presented in Table 4-5 with the ratio of waiting passengers to through passengers at time points C and G varying between 1 and 5. The ratio of waiting to through passengers is shown in the third section of the table.

We observe that as the ratio of waiting to through passengers increases, passengers experience improved reliability with the generalized cost minimization schedule compared to the 50th percentile schedule. This is because the generalized cost minimization schedule implements long holds, thus benefiting more waiting passengers than the 50th percentile schedule. Conversely, in scenario XI, which presents segments with the smallest ratios of waiting to through passengers, the generalized cost minimization schedule benefits only the onboard passengers. This is because shorter running times are scheduled on the route segments.

Scenario	XI	XII	XIII
nb (A)	8	8	6
nb(B)	0	0	0
nb(C)	8	24	30
nb(D)	0	0	0
nb(E)	8	8	6
nb (F)	0	0	0
nb (G)	8	24	30
nb (H)	0	0	0
Exp Load / trip (A-B)	8	8	6
Exp Load / trip (B-C)	8	8	6
Exp Load / trip (C-D)	16	32	36
Exp Load / trip (D-E)	8	24	30
Exp Load / trip (E-F)	16	32	36
Exp Load / trip (F-G)	8	8	6
Exp Load / trip (G-H)	16	32	36
Exp Load / trip (H-I)	8	24	30
Ratio (B)	0	0	0
Ratio (C)	1	3	5
Ratio (D)	0	0	0
Ratio (E)	1	0.3	0.2
Ratio (F)	0	0	0
Ratio (G)	1	3	5
Ratio (H)	0	0	0
Sch RT (A - B) (2)	1	1	2
Sch RT (B - C) (10)	9	11	11
Sch RT (C - D) (6)	5	4	5
Sch RT (D - E) (9)	10	10	9
Sch RT (E-F) (8)	8	9	10
Sch RT (F-G) (8)	8	10	10
Sch RT (G-H) (9)	6	6	6
Sch RT (H-I) (3)	2	2	2
Total Sch RT before layover (53)	49	53	55
Sch. Layover in min at H (8)	14	10	8
Percentile (A-B) (86%)	17%	17%	86%
Percentile (B-C) (53%)	42%	87%	87%
Percentile (C-D) (82%)	43%	15%	43%
Percentile (D-E) (60%)	73%	73%	60%
Percentile (E-F) (74%)	47%	87%	91%
Percentile (F-G) (53%)	34%	76%	76%
Percentile (G-H) (58%)	15%	15%	15%
Percentile (H-I) (90%)	49%	49%	49%
Percentage of vehicles which can run the trips within the allowed time (97%)	100%	98%	95%
Percentage of vehicles which depart A on time (89%)	94%	91%	85%
Diff. in waiting time pax-min	-29	48	108
Difference in-vehicle TT pax-min	65	34	1
Difference in total pax-min	-26	62	131
Difference in weighted pax-min	21	105	164
% Diff. in waiting time pax-min	-3%	2%	4%
% Diff. in-vehicle TT pax-min	2%	0%	0%
% Difference in total pax-min	-1%	1%	3%
% Difference in weighted pax-min	0%	1%	1%

Table 4-5 Effect of the route length

In scenario XIII, even on segments where the ratio of waiting to through passengers is less than one, long running times are scheduled on all segments in order to maintain good reliability throughout the route. This is critical because the number of waiting passengers is significant compared to the number of through passengers on two segments of the route and reliability is more difficult to maintain on longer routes. Headways are also less variable if regular holds are implemented throughout the route instead of only at certain time points. The generalized cost minimization schedule shows a saving of 34% in excess waiting time, no difference in excess in-vehicle time, and an 18% savings in excess total weighted time compared with the 50th percentile schedule.

Comparing the similar demand patterns on short routes in scenarios III, IV and V, we may conclude that schedules on long routes are also sensitive to the downstream ratio. For example, we observe that the 86th percentile is implemented on the first segment of scenario XIII whereas the 17th percentile was implemented in the first segment of scenario V. This is partly because more passengers board on later segments in scenario XIII.

In conclusion, when the route is longer (unreliability propagates more easily on longer routes), the generalized minimization schedule shows even more benefits over the 50th percentile schedule. This is especially true when there are concentrated peaks of demand on the route as shown in scenario XIII.

4.7. More realistic scenarios

The demand patterns in sections 4.1 through 4.6 are fairly extreme but they demonstrated that the generalized cost minimization showed benefits over the 50th percentile schedule. This section will compare the 50th percentile schedule with the generalized cost minimization schedule using more realistic examples. This section first considers short routes and then long routes

4.7.1. Short routes

Table 4-6 presents several demand patterns on a four-segment route. The ratio of waiting to through passengers is shown in the third section of the table.

Once again we observe that the schedule obtained with the generalized cost minimization approach is sensitive to the number of waiting passengers and through passengers. Longer scheduled segment running times result on segments where there are more waiting passengers than through passengers.

Scenario		XIV	XV	XVI
nb (A)		40	2	4
nb(B)		10	20	35
nb(C)		10	10	2
nb(D)		44	2	30
Exp Load / trip (A-B)		40	2	4
Exp Load / trip (B-C)		30	22	38
Exp Load / trip (C-D)		20	27	5
Exp Load / trip (D-E)		54	24	34
Ratio (B)		0.5	10.0	11.7
Ratio (C)		1.0	0.6	0.7
Ratio (D)		4.4	0.1	7.5
Sch RT (A - B)	(2)	1	4	4
Sch RT (B - C)	(10)	11	7	10
Sch RT (C - D)	(6)	7	4	7
Sch RT (D - E)	(9)	9	9	9
Total Sch RT before layover	(27)	28	24	30
Sch. Layover in min at E	(5)	4	8	2
Percentile (A-B)	(86%)	17%	98%	98%
Percentile (B-C)	(53%)	87%	15%	53%
Percentile (C-D)	(82%)	96%	15%	96%
Percentile (D-E)	(60%)	60%	60%	60%
Percentage of vehicles which can run the trips within the allowed time	(92%)	91%	85%	75%
Percentage of vehicles which depart A on time	(91%)	90%	82%	69%
Diff. in waiting time pax-min		40	4	66
Difference in-vehicle TT pax-min		-18	74	-52
Difference in total pax-min		22	78	14
Difference in weighted pax-min		42	80	47
% Diff. in waiting time pax-min		1%	0%	3%
% Diff. in-vehicle TT pax-min		0%	2%	-1%
% Difference in total pax-min		0%	2%	0%
% Difference in weighted pax-min		0%	1%	1%

Table 4-6 Four-segment route

In scenario XIV, most boardings occur at time points A and D. At time point D, there are over four times as many waiting passengers as through passengers. Consequently, the running time scheduled on the second and third segment of the route allows 87% and 96% of the vehicles, respectively, to complete their segment within the scheduled times in order to allow a large proportion of vehicles to depart time point D on time. Consequently, the generalized cost minimization approach saves passengers waiting time compared to the 50th percentile approach.

In scenario XV, most boardings occur at time point B. At time point B, where there are ten times more waiting than through passengers. Consequently, more running time is scheduled on segment A-B. On the other segments, short running times are scheduled because there are more through passengers than waiting passengers. Consequently, the generalized cost minimization approach creates a schedule which saves passengers a large amount of in-vehicle time compared to the 50th percentile schedule.

In scenario XVI, most boardings occur at time points B and D. At time point B, there are twelve times more waiting than through passengers and at time point D there are seven times more waiting than through passengers. Consequently, more running time is scheduled on segments A-B and C-D. On segment B-C 53% of vehicles are able to run within the allowed time in order to maintain a good level of reliability for passengers boarding downstream. The generalized cost minimization schedule saves passengers a large amount of waiting time compared to the 50th percentile schedule because longer holds occur at time points B and D.

4.7.2. Long Routes

Table 4-7 presents several demand patterns on a eight-segment route. The ratio of waiting to through passengers is shown in the third section of the table.

Scenario XVII examines the potential benefit of the generalized cost minimization approach when the load on the bus increases sharply then decreases before increasing again. In scenario XVII, the ratio is greater than 1.0 on four of the eight time points on the route. We note that the schedule obtained with the generalized cost minimization approach is sensitive to the ratio of the waiting passengers to through passengers; more running time is scheduled on segments with large ratios. The generalized cost minimization schedule saves passenger waiting time compared with the 50th percentile schedule because it induces more holds throughout the route.

In scenario XVIII, the number of waiting passengers is at least as large as the number of through passengers only at time points B and F. Consequently, we observe that more running time is scheduled on segments A-B and E-F. Also, to maintain a good level of reliability at F, a number of holds are introduced along the route with longer running times scheduled on the early segments of the route. Here, the generalized cost minimization schedule saves in-vehicle passenger time.

Scenario	XVII	XVIII	XIX
nb (A)	4	2	15
nb(B)	7	6	6
nb(C)	15	2	9
nb(D)	20	2	6
nb(E)	0	5	7
nb (F)	20	10	5
nb (G)	10	2	3
nb (H)	2	4	4
Exp Load / trip (A-B)	4	2	15
Exp Load / trip (B-C)	10	8	19
Exp Load / trip (C-D)	20	10	21
Exp Load / trip (D-E)	30	12	21
Exp Load / trip (E-F)	15	15	22
Exp Load / trip (F-G)	25	20	20
Exp Load / trip (G-H)	30	22	14
Exp Load / trip (H-I)	2	16	8
Ratio (B)	2.3	3.0	0.7
Ratio (C)	3	0.3	0.8
Ratio (D)	2	0.2	0.4
Ratio (E)	0	0.5	0.5
Ratio (F)	4	1.0	0.3
Ratio (G)	0.5	0.1	0.3
Ratio (H)	∞	0.3	1.0
Sch RT (A - B) (2)	3	2	2
Sch RT (B - C) (10)	12	10	9
Sch RT (C - D) (6)	6	4	5
Sch RT (D - E) (9)	7	10	8
Sch RT (E-F) (8)	11	9	7
Sch RT (F-G) (8)	6	6	6
Sch RT (G-H) (9)	9	6	9
Sch RT (H-I) (3)	2	2	2
Total Sch RT before layover (53)	56	49	48
Sch. Layover in min at H (8)	7	14	15
Percentile (A-B) (86%)	95%	86%	86%
Percentile (B-C) (53%)	92%	53%	42%
Percentile (C-D) (82%)	82%	15%	43%
Percentile (D-E) (60%)	15%	73%	33%
Percentile (E-F) (74%)	100%	87%	47%
Percentile (F-G) (53%)	15%	15%	15%
Percentile (G-H) (58%)	58%	15%	58%
Percentile (H-I) (90%)	49%	49%	49%
Percentage of vehicles which can run the trips within the allowed time (97%)	97%	98%	100%
Percentage of vehicles which depart A on time (89%)	77%	90%	92%
Diff. in waiting time pax-min	55	-11	-54
Difference in-vehicle TT pax-min	-21	55	105
Difference in total pax-min	63	-6	-51
Difference in weighted pax-min	61	39	24
% Diff. in waiting time pax-min	2%	-1%	-3%
% Diff. in-vehicle TT pax-min	0%	1%	2%
% Difference in total pax-min	1%	0%	-1%
% Difference in weighted pax-min	1%	1%	0%

Table 4-7 Eight-segment route

In scenario XIX, there is no time point at which there are more waiting passengers than through passengers. The schedule allows very few vehicles to complete segments within the scheduled time. The 50^{th} percentile schedule would be more beneficial for the waiting passengers since it introduces more holds than the generalized cost minimization schedule. However, the generalized cost minimization schedule provides passengers with shorter in-vehicle time.

4.7.3. Conclusion

This chapter has shown the benefits of the generalized cost minimization approach over the 50^{th} percentile on several demand patterns, focusing on the differences in total waiting and in-vehicle time between these two approaches. However, as shown in section 3.7, there is a difference between total time and excess time. As explained earlier, the only way to improve reliability and passenger service quality is by decreasing excess waiting and travel time. The "base time" cannot be improved given a particular scheduled headway because it is the time passengers have to spend on the system if they want to use it. This chapter has shown that transit planners can decrease excess times experienced by passengers by resetting schedules. Indeed, a small percentage difference in total time translates into significant improvement in excess times. The magnitude of the benefits of the generalized cost minimization schedules will depend on the characteristics of the route. However, the generalized cost minimization approach will always be more beneficial than traditional approaches such as the 50^{th} percentile.

Chapter 5. Chicago Transit Authority Route 85 Application

This chapter provides a second application of the scheduling method discussed previously to CTA Route 85. Section 5.1 describes CTA Route 85 and section 5.2 analyses it during the AM Peak application period. The result of different scheduling approaches will be presented in sections 5.3 through 5.5. The costs of each approach are then compared in section 5.6.

The objectives of this chapter are twofold:

- To investigate the current reliability of CTA Route 85
- To provide a practical demonstration of the methods presented in Chapter 4

5.1. Route 85 Characteristics

Route 85 was chosen for several reasons:

- It appears to have some segments with too much scheduled running time and others with not enough scheduled running time based on recent AVL data[11],
- It is a high frequency route, i.e. the headways are 10 minutes or less in the peak period,
- It is considered a "key route"[12] by the CTA Service Standards, providing an extra incentive to improve reliability on this route.

5.1.1. Route Description

CTA Route 85 runs seven miles north-south on Central Avenue (5600W) from Byrn Mawr (5600N) to Harrison St. (600S). Route 85 connects with two of the six CTA rail lines that serve the Loop, numerous East-West bus routes serving the Loop and northern areas of the city and three Metra Lines serving the Loop. A schematic of Route 85 including the connections with the rail and Metra lines is shown in Figure 5-1. Operators begin and end their runs at Byrn Mawr

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[11] End-to-end running time analysis webpage on CTA intranet, Michael Haynes, CTA

[12] "Key" routes and "support" routes define the CTA bus system. Key routes provide the backbone of CTA service. They include the most productive bus routes, plus additional routes to provide basic geographic coverage. Support routes are the remaining routes. They support the rail and key bus network by serving a variety of important specialized functions that all enhance the quality of service and improve market share. Two-thirds of all CTA rides are taken on the bus system. Key bus routes provide nearly half (47%) of all CTA rides. [CTA Service Standards]

and Elston, the route's northern terminus. The CTA provides service throughout the day between Harrison and Byrn Mawr except between 2:30 and 3:30 am.

Figure 5-1 CTA Route 85

5.1.2. Route Segment Description

There are 9 time points on the route Northbound and 10 time points Southbound. The reason for the extra time point (JpkBl2) Southbound is historical; JpkBl2 was used as a holding point. JpkBlu and JpkBl2 are actually physically the same time point but since slack time was always scheduled at that time point, CTA defined a second time point. JpkBl2 is situated only 1.4 miles south of the Northern terminal of Route 85. In this chapter we will not include the time point JpkBl2 since it is physically the same time point as JpkBlu. If reliability needs to be improved at JpkBlu by holding, we will allocate more running time on the previous segment.

Southbound, the time points are: (1) Byrn Mawr and Elston St. (Bm Els), (2) Jefferson Park terminal Blue Line (JpkBlu), (3) Irving Park and Central Ave. (IrvCen), (4) Belmont St. and Central Ave. (BelCen), (5) Fullerton St. and Central Ave. (FulCen), (6) North St. and Central Ave. (NorCen), (7) Chicago St. and Central Ave. (ChiCen), (8) Lake St. and Central Ave. (LakCen) and (9) Harrison Street and Central Ave. (HsnCen). The lengths of each segment defined by these time points are shown in Table 5-1.

Time point Pair	Distance (in miles)
Bm Els - JpkBlu	1.4
JpkBlu - IrvCen	1.5
IrvCen - BelCen	1.0
BelCen - FulCen	1.0
FulCen - NorCen	1.0
NorCen - ChiCen	1.0
ChiCen - LakCen	0.5
LakCen - HsnCen	1.0

Table 5-1 Route Segment Lengths

It should be noted that the distance between time points is approximately the same (about one mile) except for the two first segments of the route (Southbound) which have a length of about 1.5 miles each, and the next to last segment (Southbound) which has a length of 0.5 miles. Overall, the segments on Route 85 are short. As seen in the literature review, time points should generally be located at stops at or following which the number of boarding passengers is high relative to the number of through passengers. However, time points in the CTA bus network have been defined historically and do not necessarily comply with these principles.

5.1.3. Ridership

Figures 5-2 and 5-3 present the average boardings per trip during winter 2005 (from December 5, 2005 to June 23, 2006) throughout a weekday of operation Southbound and Northbound respectively.

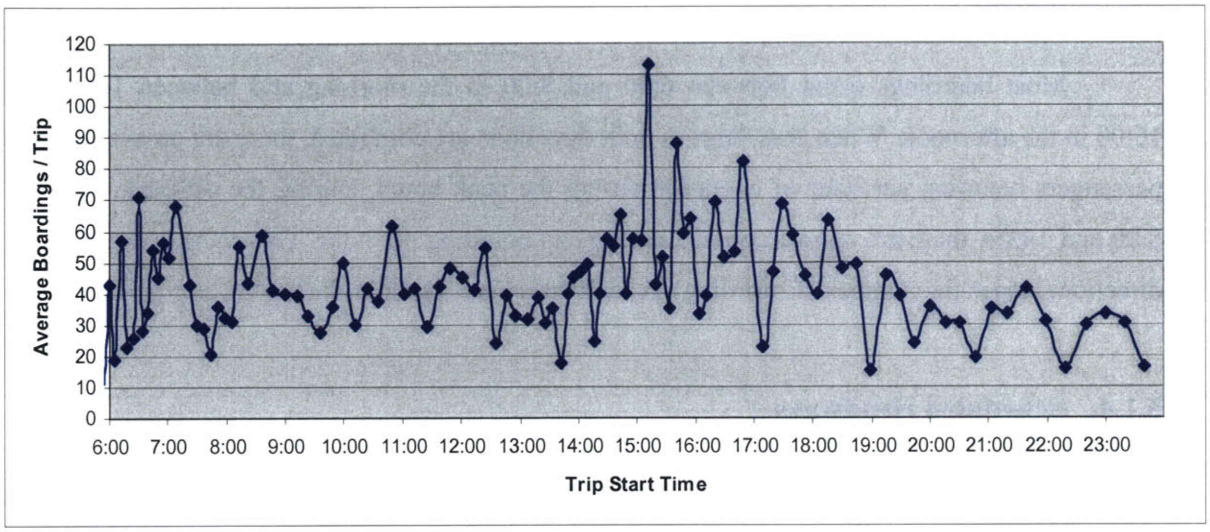


Figure 5-2 Average Boarding /Trip (Southbound)

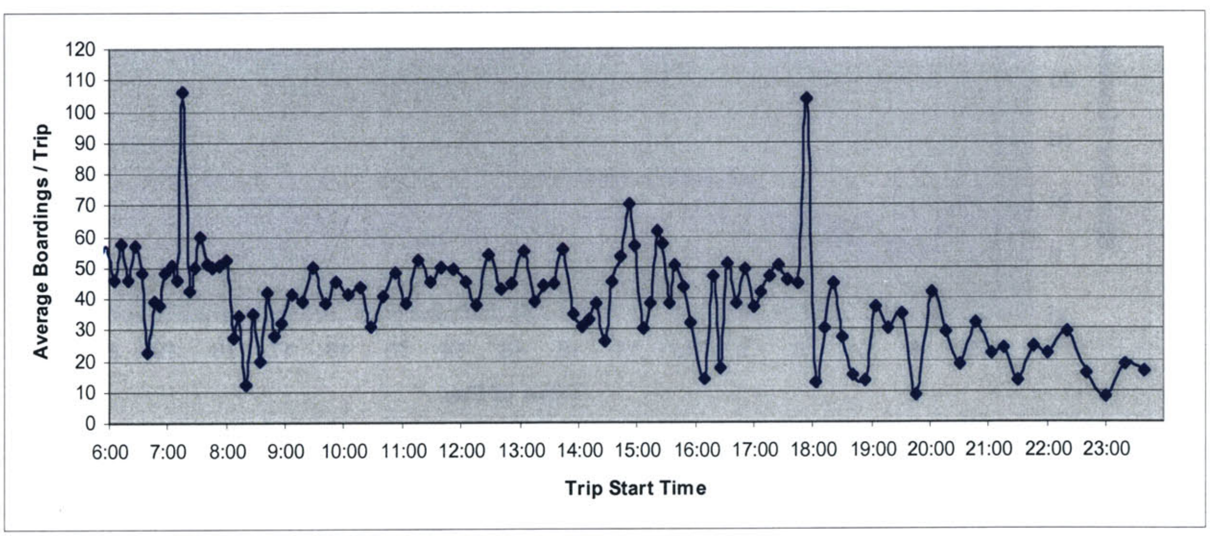


Figure 5-3 Average Boarding /Trip (Northbound)

We note that in both directions the number of boardings is highly variable from one trip to the next. This is especially true in the PM peak period which seem less reliable than the AM peak period. This is probably due to bus bunching. The graphs also indicate that it is often the same trips which are bunched, since the graphs present the average number of boardings per trip over a seven-month period. We can surmise that on Route 85 bus bunching often occurs due to specific operator behaviors.

Most boardings occur between 6:00 and 8:00 in the morning and between 14:00 and 16:00 in the afternoon. When boardings in both directions are combined, there are on average 850 passengers boarding per hour of operation during the peak hours. During the off-peak, between 8:00 and 14:00, there are on average 450 passengers boarding per hour. This route is not strongly directional since the number of boardings in each direction is similar during the two peak periods.

5.1.4. Scheduled Headways

Figures 5-4 and 5-5 show the scheduled (Southbound) headways at Bm Els and at HsnCen (Northbound) during winter 2005.

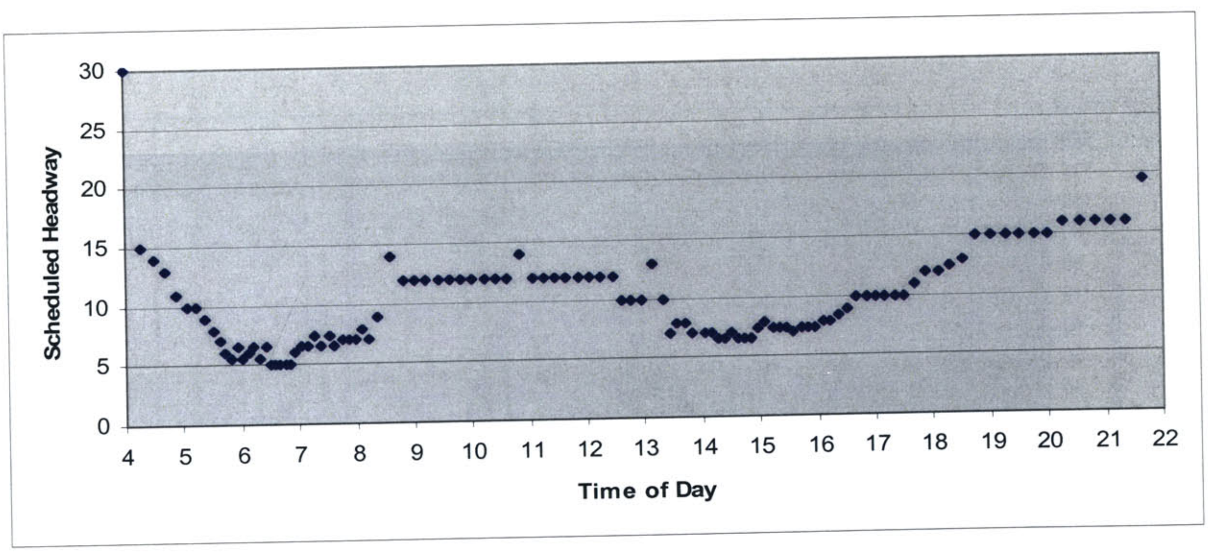


Figure 5-4 Scheduled headway at Bm Els (Southbound)

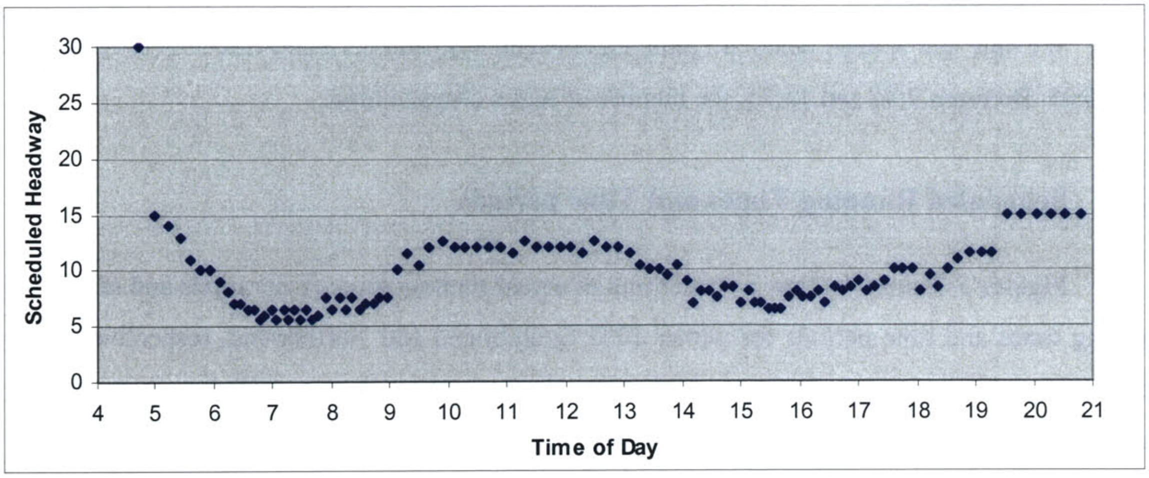


Figure 5-5 Scheduled headway at HsnCen (Northbound)

Buses run every 6 to 12 min except for night owl service which operates at 30 minute intervals. We observe that the scheduled headways show some variance within time periods; probably due to CTA taking advantage of opportunities to save resources. However, this approach could also lead to unreliable service because varying the scheduled headways from trip to trip within a time period may well lead to bus bunching.

5.1.5. Number of buses

Figure 5-6 shows the number of buses used throughout the day during winter 2005 based on the supervisor guide produced by Hastus.

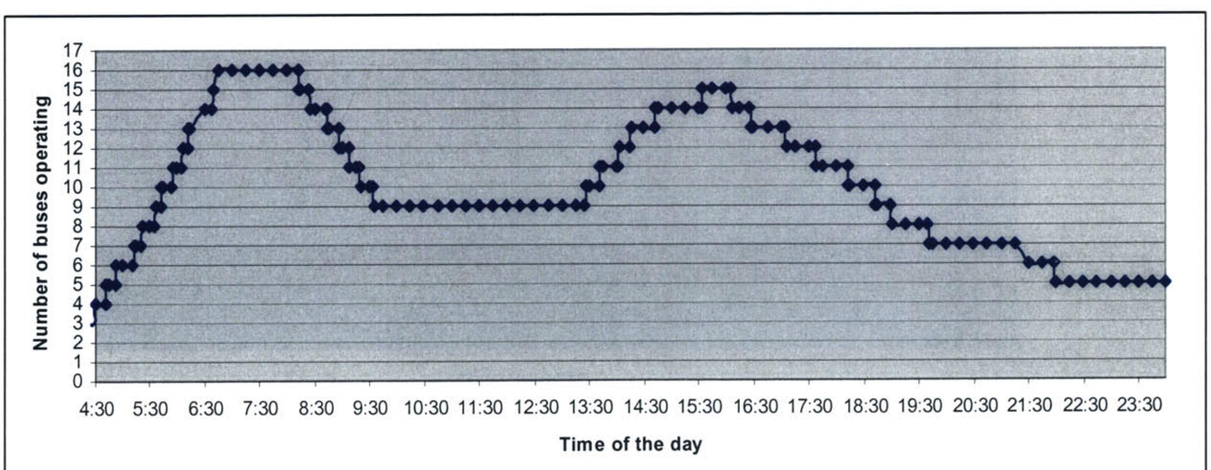


Figure 5-6 Number of buses operating

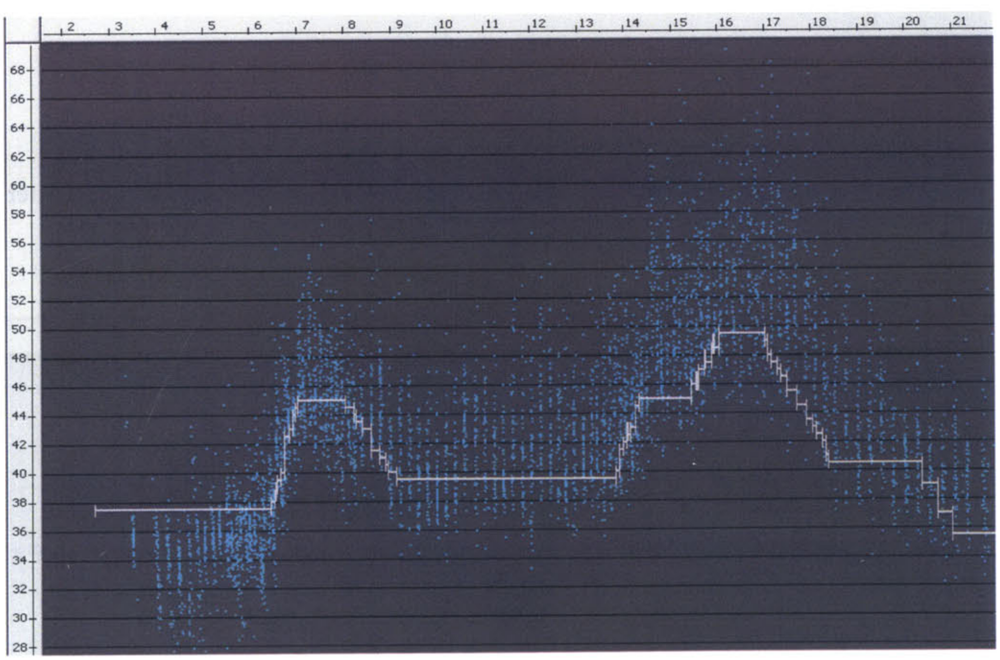
We note that sixteen buses are required between 6:45 and 8:15 and fifteen between 15:35 and 16:05. Between 9:35 and 13:25, the number of buses drops to nine.

5.1.6. Scheduled Running Times and Time periods

Figures 5-7 and 5-8 show a scatter plot of actual running time observations and scheduled running times and time periods for winter 2005 Southbound and Northbound, respectively. The scheduled running times and time periods were derived using Hastus ATP but using a 2003 dataset which contained many fewer observations than shown here.

From Figures 5-7 and 5-8, we note that there is significant variation in the scheduled running time in order to maintain the scheduled headways and the running time observations within each time period show significant variation. We observe in most time periods a fifteen-minute range of data. Having so much running time variability within a time period will affect the headway variability which leads to unreliability.

Running Time



Time of Day

Figure 5-7 Running Time data and scheduled running time (Southbound)[13]

[13] This graph was obtained using Hastus ATP

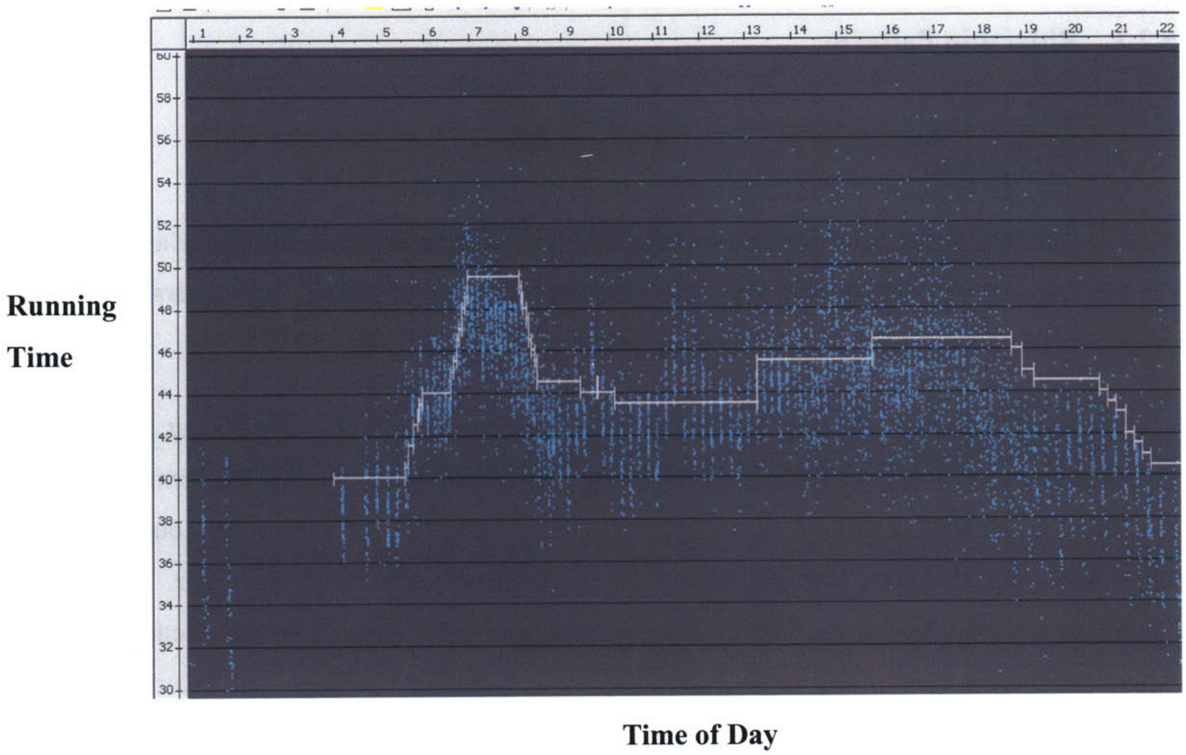


Figure 5-8 Running Time data and scheduled running time (Northbound)

Until 6:30, most of the trips can be completed within the scheduled running time in both directions. However, after 6:30, the majority of the trips cannot be completed within the scheduled running times Southbound, whereas about half of the trips can be completed on time Northbound. So there is an imbalance in the scheduled running times between the two directions. When the majority of the trips cannot be completed within the scheduled running time, and if there is not enough layover time scheduled at the end of the trip, unreliability can easily propagate to subsequent trips.

5.2. AM Peak Analysis

This section assesses the reliability of Route 85 between 7:00 and 8:00. This hour is selected because it has the most boardings during the AM Peak, as shown in section 5.1.3. In section 5.4, we will apply the scheduling approaches presented in chapter 3 to propose alternative schedules for this hour. In this section, the ridership patterns are reviewed in section 5.2.1 and the running times and headways are discussed in sections 5.2.2 and 5.2.3 respectively.

We are using one month of Automatic Passenger Count (APC) and Automatic Vehicle Location (AVL) weekday data, from April 24 to May 19, 2006 in this analysis.

5.2.1. Ridership Patterns

a) Southbound

Tables 5-2 and 5-3 show the average hourly passenger arrivals and hourly average load per trip respectively Southbound. Table 5-4 computes the ratio of through passengers at the time point to waiting passengers on the following segment.

From Table 5-2, we note that in this hour, the Southbound boardings occur primarily at four places on the route. At Jefferson Park Blue Line station where there is the connection with the Blue Line as well as with the Metra Union Pacific Northwest Line serving the Loop and many buses going North, South, East and West, 10% of the Southbound boardings occur. 14% of the boardings are recorded on the FulCen-NorCen segment where there is the connection with the Metra Milwaukee district line serving the Loop as well as four bus lines. The boardings on the NorCen-ChiCen segment where there is the connection with bus Route 70 serving the Blue, Red, Brown and Purple train lines account for 25% of the Southbound boardings. On the LakCen-HsnCen segment where there are the connections with bus Routes 20, X20 and 126 serving the Loop and the Pink Line, 10% of the boardings are recorded. We note that most (66%) of the boardings occur on the second half of the route.

	Mean Hourly Passenger Arrivals	Mean Passenger Arrivals per Trip
At Bm Els	7.3	0.7
On Bm Els - JpkBlu	15.0	1.5
At JpkBlu	37.8	3.8
On JpkBlu-IrvCen	20.0	2.0
At IrvCen	2.7	0.3
On IrvCen-BelCen	19.0	1.9
At BelCen	2.0	0.2
On BelCen-FulCen	20.0	2.0
At FulCen	0.0	0.0
On FulCen-NorCen	50.0	5.0
At NorCen	10.0	1.0
On NorCen-ChiCen	92.0	9.2
At ChiCen	6.4	0.6
On ChiCen-LakCen	17.0	1.7
At LakCen	3.0	0.3
On LakCen-HsnCen	38.0	3.8
TOTAL	**367.2**	**36.7**

Table 5-2 Mean Passenger Arrivals (Southbound)

	Average Load
Leaving Bm Els	5.4
Arriving JpkBlu	7.0
Leaving JpkBlu	7.8
Arriving IrvCen	10.6
Leaving IrvCen	10.3
Arriving BelCen	11.2
Leaving BelCen	12.2
Arriving FulCen	13.4
Leaving FulCen	13.5
Arriving NorCen	15.7
Leaving NorCen	15.6
Arriving ChiCen	25.0
Leaving ChiCen	25.7
Arriving LakCen	16.4
Leaving LakCen	16.2
Arriving HsnCen	5.2

Table 5-3 Average Load (Southbound)

	Waiting passengers on segment / Through passengers
At JpkBlu	0.8
At IrvCen	0.2
At BelCen	0.2
At FulCen	0.4
At NorCen	0.7
At ChiCen	0.1
At LakCen	0.3

Table 5-4 Ratio of waiting passengers to through passengers (Southbound)

We observe that the load at Bm Els averages 5.4 passengers because passengers can board at the Forest Glenn garage situated before Bryn Mawr and Elston. The route segments with the heaviest load are NorCen-ChiCen and ChiCen-LakCen. The load on the bus increases from the starting terminal, Bm Els, until ChiCen and then decreases from ChiCen to the terminal at HsnCen. In the AM Peak hour of operation, Route 85 Southbound can be categorized as a cross-town route as passengers board and alight all along the route.

b) Northbound

Tables 5-5 and 5-6 show the average hourly passenger arrivals and hourly average load per trip respectively Northbound. Table 5-7 computes the ratio of through passengers at the time point to waiting passengers on the following segment.

During this period, we observe that there are more passengers (54 boardings per trip) traveling Northbound than Southbound. HsnCen – LakCen generates 25% of the Northbound boardings because of the connections on this segment to four bus routes serving the Loop. Boardings occurring at LakCen and the LakCen-ChiCen segment, where there are the connections with the Green line and the Metra Union Pacific West line serving the Loop, account for 12% of the Northbound boardings. 13% of the Northbound boardings are recorded on the ChiCen-NorCen segment where there is the connection with bus Route 70. The FulCen-BelCen segment, where there are connections with Bus routes 74 and 76 serving the Blue, Red, Brown and Purple train lines, accounts for 9% of the boardings. We note that most of the boardings occur on the first half of the route with 67% of the boardings occurring before FulCen.

	Mean Hourly Passenger Arrivals	Mean Passenger Arrivals per Trip
At HsnCen	17.7	1.8
On HsnCen - LakCen	132.3	13.2
At LakCen	30.7	3.1
On LakCen - ChiCen	33.5	3.4
At ChiCen	19.3	1.9
On ChiCen - NorCen	68.3	6.8
At NorCen	22.0	2.2
On NorCen - FulCen	36.6	3.7
At FulCen	19.3	1.9
On FulCen - BelCen	46.7	4.7
At BelCen	14.3	1.4
On BelCen - IrvCen	35.3	3.5
At IrvCen	0.0	0.0
On IrvCen - JpkBlu	25.2	2.5
At JpkBlu	16.3	1.6
On JpkBlu - Bm Els	20.7	2.1
TOTAL	**538.2**	**53.8**

Table 5-5 Mean Passenger Arrivals (Northbound)

	Average Load
Leaving HsnCen	1.8
Arriving LakCen	15.1
Leaving LakCen	18.1
Arriving ChiCen	18.8
Leaving ChiCen	20.2
Arriving NorCen	21.6
Leaving NorCen	22.3
Arriving FulCen	19.5
Leaving FulCen	20.4
Arriving BelCen	24
Leaving BelCen	19.3
Arriving IrvCen	20.5
Leaving IrvCen	19.5
Arriving JpkBlu	8.1
Leaving JpkBlu	7.3
Arriving Bm Els	6.6

Table 5-6 Average Load (Northbound)

	Waiting passengers on segment / Through passengers
At LakCen	0.4
At ChiCen	0.5
At NorCen	0.3
At FulCen	0.3
At BelCen	0.2
At IrvCen	0.1
At JpkBlu	0.5

Table 5-7 Ratio of waiting passengers to through passengers (Northbound)

Northbound, the load stays constant for most of the route. From LakCen until IrvCen, the average vehicle load is about 20 passengers. As shown, most passengers board on the first segment of the route Northbound and alight on the two last segments of the route. Route 85 can be categorized as a crosstwon type of route between 7:00 and 8:00, Northbound.

To summarize, Southbound passengers mostly board on the second half of the route with the load increasing from the terminal to ChiCen and then decreasing. Northbound passengers mostly board on the first half of the route and especially on the first route segment, HsnCen-LakCen, and mostly alight on the two last route segments. The load Northbound stays relatively constant throughout the route until IrvCen. The heaviest direction is Northbound with a total of

539 passengers boarding versus 368 passengers boarding Southbound. Therefore, Route 85 is directional Northbound in the AM Peak. (Route 85 is one of the heavier routes of the Chicago Transit Authority system. Out of 141 CTA bus routes, 111 routes have an hourly boarding rate less than or equal to Route 85's hourly boarding rate[14]).

By observing Tables 5-4 and 5-7, we note that the number of through passengers is always greater than the number of waiting passengers. In addition, the segments are very short on Route 85, as noted in section 5.1.2. When the number of through passengers at time point is very large compared to the number of waiting passengers on the following segment, there is no need to hold the bus regularly along the route and consequently, having time points so close to each other does not seem to be justifiable on Route 85.

5.2.2. Running times

Tables 5-8 and 5-9 show the running time analysis between 8:00 and 9:00 Southbound and Northbound respectively. The second column shows the scheduled running times on each segment of the route. The third column computes the percentage of buses which complete the segment (from departing the starting time point to arriving at the next time point) within the scheduled running time. The fourth column indicates the proportion of vehicles which depart the starting time point of each segment on time. The fifth column presents the mean segment running times, from the time point departure to the arrival at the next time point. The sixth column shows the coefficient of variation of the running time (from departure to arrival) indicating the segment running time variability. The seventh column shows the mean running time, between departures at successive time points, in order to gauge whether "holding" is occurring at each time point.

We note that the actual mean round-trip "cycle" time is 100.3 minutes and the scheduled round-trip time varies between 104 and 111.5 minutes for this period. Thus, on average, there is currently enough time scheduled for the round-trip. Also, on most segments, the running time is not highly variable, as evidenced by the small segment running time coefficients of variation.

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[14] Report "Route Summary – by Schedule", Michael Haynes, for the Winter Pick 2005

Southbound	Sch. RT (min)	% of vehicles which run the segment within the sch RT	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Arrive) (min)	COV RT (From Depart to Arrive)	Mean RT (From Depart to Depart) (min)
Bm Els– JpkBlu	8	96%	2%	5.6	0.18	5.7
JpkBlu – IrvCen	7	80%	10%	6.1	0.16	7.2
IrvCen – BelCen	5.5	98%	16%	3.5	0.20	4.5
BelCen– FulCen	5	88%	34%	3.9	0.23	5.3
FulCen– NorCen	4.5	82%	36%	3.8	0.17	5.1
NorCen– ChiCen	6	75%	29%	5.3	0.18	6.4
ChiCen– LakCen	3	40%	25%	2.7	0.20	3.5
LakCen-HsnCen	4.5	18%	23%	4.8	0.12	
One-Way RT	43.5	17%		35.8		42.5
Lay. at HsnCen	6					4.9
Sch.One-Way Trip	49.5	80%				47.3

Table 5-8 Running times in the AM Peak (Southbound)

Northbound	Sch. RT (min)	% of vehicles which run the segment within the sch RT	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Arrive) (min)	COV RT (From Depart to Arrive)	Mean RT (From Depart to Depart) (min)
HsnCen-LakCen	7	85%	11%	5.9	0.14	7.3
LakCen - ChiCen	4	96%	18%	2.5	0.22	3.5
ChiCen - NorCen	6	86%	33%	5.2	0.13	6.4
NorCen - FulCen	5.5	>100% (100%= 5.4)	21%	3.8	0.17	4.9
FulCen - BelCen	5	59%	38%	4.7	0.16	5.8
BelCen - IrvCen	7	96%	19%	4.7	0.21	5.8
IrvCen - JpkBlu	9	73%	53%	8.1	0.16	10.0
JpkBlu – Bm Els	6	97%	24%	4.1	0.15	
One-Way RT	49.5	15%		39.1		47.8
Lay. at Bm Els	5-12.5					5.2
Sch.OneWay Trip	54.5-62	23%-71%				53.0

Table 5-9 Running times in the AM Peak (Northbound)

We note that there is enough running time scheduled in each direction, since, the mean running time Southbound is 42.5 minutes while the scheduled running time is 43.5 minutes and the scheduled running time Northbound is 49.5 minutes while the mean running time is 47.8 minutes. Currently, 80% of the Southbound trips and 23% to 71% of the Northbound trips can be completed within the allowed time. But since unreliability has propagated from the previous trips, only 2% of the Southbound trips and 11% of the Northbound trips actually start on time.

We note that the current schedule allows a large proportion of vehicles to run most segments within the scheduled time. Southbound, more than 75% of the vehicles can complete each of the first six segments within the scheduled running time. Northbound, the scheduled running times allow at least 60% of the vehicles to complete each segment within the allowed time. In fact, for the NorCen-FulCen segment, the running time is scheduled at a level where all vehicles can complete their segments within the scheduled running time. Clearly, on most segments, there is too much running time scheduled since the number of through passengers is larger than the number of waiting passengers. Yet, even with the very long scheduled segment running times, we can see from the previous sections that this route is not reliable between 7:00 and 8:00.

From Tables 5-8 and 5-9, we observe that the holding times at time points are quite large, often larger than necessary. Indeed, the mean time (from the departure time at the starting time point of the segment to the departure time at the next time point) is often longer than the scheduled segment running time even though the bus could have departed on time, i.e. even though the mean running time from the departure time at the starting time point of the segment to the arrival time at the next time point is shorter than the scheduled running time. For example, it seems that that operators hold at NorCen Southbound even if they are late. Due to the inconsistent nature of departures from time points, headways will be variable which leads to unreliability for the waiting passengers.

As previously stated, even though a large proportion of trips can complete their trips within the allowed time and the average one-way running times and average half-trip times are shorter than scheduled, only few trips depart their next trip or each time point on time. This is because trip distributions are very wide and unreliability has often propagated from the previous trips. However, without the apparent (long) holds occurring at time points, trip time distributions would be tighter and 99% of the Southbound trips and 100% of the Southbound trips could be completed within the allowed time. Thus reliability would be improved for the waiting passengers since a larger proportion of vehicles would be able to depart their next trip and each time point on time. This would lead also to less variable headways.

5.2.3. Headways

Figures 5-4 and 5-5 show that the scheduled headways varied between 5.5 and 7.5 minutes between 7:00 and 8:00. However, the mean headway for the waiting passengers is 6.5 minutes since the average round-trip time is 103.6 minutes and there are 16 buses in operation. Table 5-10 shows the variability of the headways departing and arriving at each time point.

Southbound	St.Dev (Act Hway/ Sch Hway)	COV (Act Hway/ Sch Hway)	Northbound	St.Dev (Act Hway/ Sch Hway)	COV (Act Hway/ Sch Hway)
Leaving Bm Els	0.4	0.45	Leaving HsnCen	0.3	0.30
Arriving JpkBlu	0.4	0.44	Arriving LakCen	0.4	0.40
Leaving JpkBlu	0.4	0.40	Leaving LakCen	0.4	0.41
Arriving IrvCen	0.4	0.48	Arriving ChiCen	0.4	0.44
Leaving IrvCen	0.4	0.45	Leaving ChiCen	0.4	0.46
Arriving BelCen	0.4	0.46	Arriving NorCen	0.5	0.52
Leaving BelCen	0.4	0.47	Leaving NorCen	0.5	0.53
Arriving FulCen	0.5	0.61	Arriving FulCen	0.5	0.53
Leaving FulCen	0.5	0.51	Leaving FulCen	0.5	0.49
Arriving NorCen	0.5	0.54	Arriving BelCen	0.4	0.47
Leaving NorCen	0.5	0.61	Leaving BelCen	0.5	0.49
Arriving ChiCen	0.6	0.68	Arriving IrvCen	0.4	0.45
Leaving ChiCen	0.6	0.67	Leaving IrvCen	0.4	0.39
Arriving LakCen	0.6	0.73	Arriving JpkBlu	0.3	0.36
Leaving LakCen	0.6	0.76	Leaving JpkBlu	0.4	0.43
Arriving HsnCen	0.7	0.81	Arriving Bm Els	0.4	0.48

Table 5-10 Headway variability

As expected, the headways are highly variable due to the variability of time vehicles spend on each segment of the route. Consequently passengers experience poor reliability. The variability is higher Southbound because fewer Southbound vehicles can depart the terminal on time. The headways are also very variable leaving the terminals Bm Els and HsnCen because vehicles are inheriting the unreliability built up from the beginning of the day. Headway variability can propagate from one trip to the next if enough recovery time is not scheduled at the end of the trip. The headway variation increases Southbound while Northbound, the variation increases and then seems to decrease slightly on the second half of the route.

It is generally expected that the variability of the headways increases over a segment and this is true on all segments except on Bm Els-JpkBlu, FulCen-BelCen, BelCen-IrvCen and IrvCen-JpkBlu where the variability of the headway decreases slightly. Finally, we expect that the variability of the headway should decrease between the headway arriving and the headway departing from the time point. Indeed, the schedule-based holding strategy is supposed to decrease the variability of the departure-to-departure time vehicles spend on each segment of the route. However, we note that Southbound at BelCen, NorCen and LakCen and Northbound at LakCen, ChiCen, NorCen, BelCen and JpkBlu, the variability of the departing headway is slightly larger than the variability of the arriving headway. This indicates that schedule-based holding is not consistently observed on Route 95E.

5.3. Current Situation with Schedule-Based Holding Strategy

Tables 5-11 and 5-12 present the modeled mean running times and headway variability if the current schedule was operated on Route 85 but with strict enforcement of schedule-based holding.

It is important to evaluate the current schedule independent of current operator behavior in order to provide a "base" case of the schedule to compare with the schedules obtained with other approaches discussed previously assuming that the schedule-based holding strategy is enforced. Under this scenario, approximately 99% of Southbound trips and 100% of Northbound trips are projected to be completed within the allowed time. Consequently, enforcing the schedule-based holding allows a much larger proportion of vehicles to start their next trip on time.

The mean times vehicles spend on the FulCen-NorCen and IrvCen-JpkBlu segments are lower than the current mean segment time because unnecessarily long holds are eliminated. On the hand, on segments such as Bm Els - JpkBlu or NorCen - FulCen, the mean time vehicles spend on these segments with the schedule-based holding strategy are longer since vehicles do not leave time points early. Overall, with the schedule-based holding strategy, the mean half-cylce time distributions are projected to be tighter than currently and the mean half-cycle times are shorter than scheduled. Consequently, the number of vehicles which can depart their subsequent trip on time increases significantly.

Southbound	Sch. RT. (min)	% of vehicles which run the segment within the sch RT	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Depart) (min)	COV (Hway) at the starting TP	COV (Hway) at the ending TP
Bm Els - JpkBlu	8	96%	100%	8.0	0.00	0.23
JpkBlu - IrvCen	7	80%	94%	7.2	0.03	0.21
IrvCen - BelCen	5.5	98%	59%	5.3	0.12	0.19
BelCen-FulCen	5	88%	92%	5.2	0.06	0.21
FulCen- NorCen	4.5	82%	69%	4.6	0.13	0.20
NorCen-ChiCen	6	75%	43%	6.2	0.14	0.24
ChiCen-LakCen	3	40%	37%	3.4	0.18	0.21
LakCen-HsnCen	4.5	18%	16%	5.1	0.20	0.24
One-way RT	43.5			45.1		
Lay. at HsnCen	6			4.1		
One-way trip	49.5			49.2		

Table 5-11 Current schedule with on-time departure enforcement (Southbound)

Southbound	Sch. RT. (min)	% of vehicles which run the segment within the sch RT	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Depart) (min)	COV (Hway) at the starting TP	COV (Hway) at the ending TP
HsnCen-LakCen	7	85%	99%	7.2	0.01	0.18
LakCen-ChiCen	4	96%	65%	3.9	0.09	0.15
ChiCen-NorCen	6	86%	85%	6.2	0.06	0.18
NorCen- FulCen	5.5	100%	53%	5.3	0.11	0.19
FulCen- BelCen	5	59%	87%	5.5	0.05	0.18
BelCen - IrvCen	7	96%	35%	6.6	0.14	0.25
IrvCen - JpkBlu	9	73%	85%	9.3	0.09	0.27
JpkBlu - Bm Els	6	97%	57%	4.3	0.17	0.22
One-Way RT	49.5			48.2		
Layover at Bm Els	5			6.0		
One-way trip	54.5			54.2		

Table 5-12 Current schedule with on-time departure enforcement (Northbound)

The current schedule with schedule-based holding has a mean one-way running time 2 minutes longer Southbound and 1 minute longer Northbound than for the current schedule, as shown in Tables 5-8 and 5-9. Consequently, passengers will experience longer in-vehicle travel time when the schedule-based holding strategy is enforced.

In addition, with schedule-based holding, vehicles do not leave terminals early. Thus the mean recovery time at Bm Els is increased. The fact that vehicles do not leave the time points or the terminals erratically directly affects the headways which are less variable than currently. This shows that passengers experience poor reliability on Route 85 primarily due to operator behavior. And we clearly observe the significant benefit of the schedule-based holding strategy being enforced at time points; headway variability decreases sharply between the arrival and the departure at a time point.

In conclusion, even though the schedule-based holding strategy will lengthen the passenger in-vehicle travel time, it will significantly improve reliability for the waiting passengers.

5.4. Traditional Approach

Tables 5-13 and 5-14 present the 50th percentile solution showing the scheduled running times rounded up to the next integer, the mean running time on each segment and headway coefficient of variation at each time point.

Southbound	Sch. RT. (min)	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Depart) (min)	COV (Hway) at the starting TP	COV (Hway) at the ending TP
Bm Els - JpkBlu	6	100%	6.5	0.00	0.23
JpkBlu - IrvCen	7	42%	7.1	0.15	0.25
IrvCen - BelCen	4	44%	4.2	0.18	0.24
BelCen- FulCen	4	32%	4.6	0.21	0.28
FulCen- NorCen	5	9%	4.6	0.25	0.31
NorCen-ChiCen	6	35%	6.1	0.25	0.33
ChiCen-LakCen	4	26%	3.7	0.27	0.30
LakCen-HsnCen	5	48%	5.1	0.24	0.29
One-way RT	41		41.9		
Lay. at HsnCen	10		8.8		
One-way trip	51		50.7		

Table 5-13 50th percentile running time solution (Southbound)

Northbound	Sch. RT. (min)	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Depart) (min)	COV (Hway) at the starting TP	COV (Hway) at the ending TP
HsnCen-LakCen	7	100%	7.2	0.00	0.18
LakCen-ChiCen	3	65%	3.2	0.09	0.15
ChiCen-NorCen	6	41%	6.1	0.12	0.21
NorCen- FulCen	5	40%	4.8	0.16	0.22
FulCen- BelCen	5	56%	5.4	0.13	0.21
BelCen - IrvCen	5	29%	5.4	0.18	0.27
IrvCen - JpkBlu	9	23%	9.0	0.25	0.35
JpkBlu - Bm Els	5	33%	4.3	0.28	0.31
One-Way RT	45		45.5		
Layover at Bm Els	8		7.2		
One-way trip	53		52.7		

Table 5-14 50th percentile running time solution (Northbound)

Southbound, the percentage of vehicles which can depart the starting time point of each segment on time decreases from Bm Els to NorCen because the schedule allows only 50% of vehicles to run the segments within the scheduled segment running time. Consequently, going Southbound, fewer and fewer vehicles depart each time point on time. However, the percentage of vehicles which depart the starting time point of segments NorCen-ChiCen and LakCen-HsnCen increases. On FulCen-NorCen, the 50th percentile of the segment running time distribution is equal to 4.01 minutes. Rounding up to the next integer, the segment running time implemented here for FulCen-NorCen is 5 minutes which corresponds to the 97th percentile of the segment running time distribution. Thus, since more vehicles can run segment FulCen-NorCen within the scheduled segment running time, more vehicles will be able to depart NorCen on time. Likewise, on ChiCen-LakCen, the 50th percentile of the segment running time distribution corresponds to 3.1 minutes and after rounding, 4 minutes corresponds to the 96th percentile of the segment running time distribution. Northbound, the percentage of vehicles which can depart time points FulCen and JpkBlu increases for the same reasons. On segment NorCen-FulCen, the 96th percentile of the segment running time distribution is selected and on segment IrvCen-JpkBlu, the 73rd percentile of the segment running time distribution is selected.

Setting the scheduled time at a level where (at least) 50% of the vehicles would have sufficient time to run each segment allows 100% of the trips on both directions to be completed within the allowed time. Consequently, 100% of the trips in both directions depart on time from their respective terminals.

The 50^{th} percentile solution has a mean one-way running time 3.2 minutes shorter Southbound and 2.7 minutes shorter Northbound than for the current schedule with schedule-based holding. Consequently, passengers would experience shorter in-vehicle travel time with the 50^{th} percentile schedule since less holding occurs at time points.

It should be noted that the headways are slightly more variable with the 50^{th} percentile approach compared to the current schedule with schedule-based holding. However, with the 50^{th} percentile schedule, the headways leaving the terminal have no variability since 100% of the vehicles can start their trip on time. Once again, we note the significant benefits of enforcing schedule-based holding; the headways departing time points are less variable than the arriving headways.

In conclusion, the 50^{th} percentile solution shows a good level of reliability for the waiting passengers but shortens the in-vehicle travel times compared to the current schedule with schedule-based holding enforced. Indeed, as stated earlier, too much running time is currently scheduled on many segments of the route.

5.5. Generalized cost minimization approach

Tables 5-15 and 5-16 present the schedule obtained applying the proposed generalized cost minimization approach. The schedule presented below minimizes the total weighted passenger minutes which is the sum of the passenger waiting time (weighted by 1.5) and the passenger in-vehicle time (see chapter 2 for a discussion of this approach).

The scheduled segment running times obtained with the generalized cost minimization approach are not feasible for the operators; the approach is effectively the same as eliminating time points, especially Northbound. Indeed, we note that a very small proportion of vehicles are able to depart the segments on time. The schedule has been developed this way because on most segments of this route, more passengers are onboard the vehicles than waiting for service. Furthermore all vehicles are able to depart each terminal on time. Consequently, the generalized cost minimization approach logically selects low percentiles on the segments where there are more through passengers than passengers waiting so as not to delay a significant number of through passengers by holding.

Southbound	% of vehicles which run the segment within the sch RT	Sch. RT.	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Depart)	COV (Hway) at the starting TP	COV (Hway) at the ending TP
Bm Els - JpkBlu	62%	6	100%	6.5	0.00	0.23
JpkBlu - IrvCen	41%	6	42%	6.8	0.15	0.25
IrvCen - BelCen	73%	4	14%	4.1	0.24	0.29
BelCen- FulCen	57%	4	17%	4.6	0.27	0.33
FulCen- NorCen	49%	4	5%	4.4	0.30	0.35
NorCen-ChiCen	28%	5	5%	6.0	0.33	0.40
ChiCen-LakCen	40%	3	2%	3.4	0.37	0.40
LakCen-HsnCen	58%	5	1%	5.1	0.38	0.43
One-way RT		37		40.8		
Lay. at HsnCen		15		10.9		
One-way trip		52		51.7		

Table 5-15 Generalized cost minimization solution (Southbound)

Northbound	% of vehicles which run the segment within the sch RT	Sch. RT.	% of vehicles which depart the starting TP on time	Mean RT (From Depart to Depart)	COV (Hway) at the starting TP	COV (Hway) at the ending TP
HsnCen-LakCen	47%	6	100%	6.7	0.00	0.18
LakCen-ChiCen	15%	2	24%	3.1	0.16	0.20
ChiCen-NorCen	29%	5	0%	5.8	0.20	0.26
NorCen- FulCen	45%	4	0%	4.3	0.26	0.30
FulCen- BelCen	59%	5	1%	5.3	0.30	0.33
BelCen - IrvCen	60%	5	1%	5.3	0.33	0.39
IrvCen - JpkBlu	73%	9	1%	8.7	0.39	0.46
JpkBlu - Bm Els	37%	4	4%	4.3	0.45	0.47
One-Way RT		40		43.5		
Layover at Bm Els		12		8.1		
One-way trip		52		51.6		

Table 5-16 Generalized cost minimization solution (Northbound)

Even though the ratio of waiting passengers to through passengers is less than one at BelCen (Southbound), the running time on the IrvCen-BelCen segment allows 73% of vehicles to complete the segment within the allowed time. The proportion of vehicles which can run the segment within the scheduled time seems large but it is only because the distribution of running times on these segments is tight and is a result of rounding up to the next integer number of minutes.

We observe that the running time percentiles on segments in the second half of each direction are very large even though the ratio of waiting passengers to through passengers is low on these segments. This is partly due to the fact that the running time distributions are also very tight on these segments and rounding up to the next integer results in larger percentiles on these segments. Also, the running time scheduled on these segments can be large without disadvantaging through passengers. The vehicles are so late that they will arrive at these time points later than the scheduled departure time from the time points and consequently will not hold at these time points. We observe that a very small percentage of vehicles can depart on time from time points on the second half of the route in either direction.

We note that with the generalized cost minimization approach, the mean running times in both directions are longer than scheduled since less time is scheduled on segments in order to have shorter holds which would delay the lowest number of through passengers. Trips arrive on average 3.8 minutes late at HsnCen and 3.6 minutes late at Bm Els. However, even though trips arrive late at terminals, 100% of them are able to complete their trips within the allowed time (including recovery) and consequently 100% of the trips are able to start their next trip on time. The mean recovery time at HsnCen is 11 minutes and the mean recovery time at Bm Els is 8 minutes. More recovery time has been scheduled at HsnCen because the Northbound direction is the heaviest.

Compared to the 50^{th} percentile schedule, the generalized cost minimization schedule allows fewer vehicles to complete the route segments within the scheduled time. Thus, the scheduled running time is shorter with the generalized cost minimization schedule in both directions. Consequently, the mean running times are also shorter since fewer holds will occur at time points. The mean running time is one minute shorter Southbound and two minutes shorter Northbound. Since fewer holds are occurring, we expect the generalized cost minimization schedule to cost less to the onboard passengers.

However, because less running time is scheduled on segments, the projected headways of the generalized cost minimization schedule are more variable than the projected headways with the 50^{th} percentile schedule. Implementing the generalized cot minimization schedule is almost like implementing a schedule without time points along the route, especially Northbound. Indeed, even though the schedule-based holding strategy is enforced, we note that the variability of the headways does not decrease leaving time points as it did in the preceding approach because not enough time is scheduled on the route segments to induce holding.

In short, implementing the 50th percentile schedule provides better reliability for the waiting passengers than the generalized cost minimization approach but would increase the passengers in-vehicle time and overall waited passenger time slightly.

5.6. Cost Comparison

Table 5-17 shows the total and excess costs for the passengers and for the CTA in dollars and in minutes for each schedule presented in the previous sections. The table shows, as well, the percentage cost difference compared to the current situation. When the percentage is positive, it represents a saving associated with the projected solution compared to the current situation. The costs are calculated as explained in Chapter 2 with the following cost parameters:

Waiting time cost per passenger hour= $12/passenger-hour

In-vehicle travel time cost per passenger hour= $8/passenger-hour

Operating cost per hour of operation=$76/passenger-hour[15] *(excluding pension costs)*

	Current situation	Current schedule with sch. based holding	Traditional Approach (50%)	Generalized cost minimization approach
Pax Waiting Time Cost	$744	$584	$597	$623
In-veh TT cost	$1,622	$1,666	$1,562	$1,495
Operating Cost	$2,096	$2,096	$2,096	$2,096
TOTAL COST	**$4,462**	**$4,346**	**$4,255**	**$4,214**
Waiting time in pax-min	3,721	2,921	2,983	3,115
In vehicle TT in pax-min	12,162	12,492	11,712	11,213
TOTAL PAX-MIN	**15,882**	**15,413**	**14,695**	**14,327**
TOTAL WEIGHTED PAX-MIN	**17,743**	**16,784**	**16,187**	**15,885**
% difference in waiting time		21%	20%	16%
% difference in in-vehicle TT		-3%	4%	8%
% difference in pax-min		3%	7%	10%
% difference in weighted pax-min		5%	9%	10%
Excess waiting time in pax-min	767	64	127	239
Excess in-vehicle time in pax-min	2275	1870	1116	671
Excess total time	**3042**	**1934**	**1242**	**910**
Excess total weighted time	**3425**	**1966**	**1306**	**1030**
% difference in excess waiting time		92%	83%	69%
% difference in excess in-vehicle TT		18%	51%	70%
% difference in excess pax-min		**36%**	**59%**	**70%**
% difference in excess weighted pax-min		**43%**	**62%**	**70%**

Table 5-17 Cost Comparison

[15] *Source: 2007 CTA Budget Recommendation p.139: Revenue Hours/Operating Cost= $76/hr of operation*

First, we observe that any of the scheduling approaches substantially decreases the passengers waiting cost for route 85. The generalized cost minimization schedule saves the least waiting passenger minutes because fewer holds are implemented in the schedule so as not to delay through passengers who are always more than waiting passengers. The 50th percentile schedule or the current schedule with schedule-based holding strategy present the lowest costs for the waiting passengers (83%-92%). The current schedule with schedule-based holding also significantly improves reliability for the waiting passengers compared to the current situation. This indicates that passengers experience long waiting times on Route 85 largely as a result of operator behavior. The result is headway variability since each operator is not behaving consistently at time points.

The passenger's in-vehicle time using the current schedule with schedule-based holding is longer than passengers would experience in the two alternative approaches. Too much running time is scheduled since the waiting passengers are few compared to the through passengers.

As expected, the generalized cost minimization approach schedule saves passengers travel time compared to the 50th percentile schedule. Even though, the generalized cost minimization schedule lengthens the excess waiting time by 89%, it reduces excess in-vehicle time compared to the 50th percentile schedule by 40%. The schedule obtained with the generalized cost minimization approach saves 332 excess passenger minutes or 276 excess weighted passenger minutes compared to the 50th percentile schedule. This represents a saving of 27% in excess total passenger minutes and 21% in excess weighted passenger minutes.

In short, we have verified that the guidelines offered in chapter 4 can be applied to Route 85. The generalized cost minimization schedule offers savings in total travel time compared to the 50th percentile schedule.

Adding an extra bus to the route would not show any significant improvement in the reliability of the route since with the proposed schedule all vehicles are already able to depart their next trip on time.

In conclusion, implementing the generalized cost minimization schedule on Route 85 between 7:00 and 8:00 would improve the reliability and the overall service quality for passengers on the route as long as schedule-based holding is enforced. We have shown that without the strict enforcement of the schedule-based holding strategy, the headways become more variable which triggers greater unreliability.

Chapter 6. Summary and Conclusions

This chapter summarizes this research and presents conclusions on the potential for improving high-frequency bus service reliability through better scheduling. Section 6.1 summarizes the research. Then section 6.2 provides a series of recommendations to the CTA. Finally, section 6.3 presents suggestions for future research.

6.1. Summary of the research

Developing a schedule for high-frequency bus routes involves balancing the costs to the passengers in terms of passenger waiting time and in-vehicle time and the cost to the transit agency. Passengers are interested in short travel times and in short and reliable waiting times. In order to assess the trade-off between trip speed and reliability, transit planners need to follow a clear scheduling process; i.e., a series of steps the scheduler follows to create a schedule.

This thesis develops a scheduling process based on a model which explicitly projects and evaluates the tradeoffs between overall travel time and reliability. The model uses Automatic Vehicle Location and Automatic Passenger Count data and is based on two critical hypotheses: (i) consecutive bus vehicle trips are independent and (ii) consecutive segment running times for a particular bus trips are independent. These two hypotheses will not be true in all cases but were shown to be true on the two CTA bus routes analyzed, 95E and 85. By simulating the running time distributions and headway variability of any proposed schedule, the model estimates the cost of the schedule for waiting passengers, onboard passengers and the transit agency. The scheduling process involves finding the time point schedule which minimizes the total cost with the help of the model.

The scheduling process is applied to two CTA bus routes; Route 95E and 85. For each route, the schedule which minimizes the total passenger cost was determined. The operating cost of the proposed schedule on each route is the same as for the current schedule because the same number of buses is used. The schedules obtained with the generalized cost minimization approach showed improved reliability and overall passenger service quality compared to the current schedule in both routes as well as compared to traditional approaches.

A sensitivity analysis showed that in most cases the generalized cost minimization schedule can significantly improve reliability and overall passenger service quality over traditional approaches.

6.2. Recommendations

This section presents recommendations specific to CTA Routes 95E and 85. Subsequently, section 6.2.3 presents general recommendations related to setting time point running times for high-frequency bus routes.

6.2.1. Route 95E Recommendations

As noted in sections 3.3 and 3.6, one of the reasons for the unreliability on Route 95E appears to be operator behavior. The existing nominal schedule-based holding strategy is not strictly observed on Route 95E. This leads to headway variability which triggers unreliability. As such, we advise CTA to reinforce the schedule-based holding practice on Route 95E.

From the analysis in section 3.1.6, we also recommend that CTA redesign the running time periods, especially Westbound in the afternoon when currently a single period is defined from 13:45 to 17:14. This time period includes part of the off-peak and part of the peak period. Having a single time period for two different operating conditions does not recognize the significant running time variations that exist during the single time period which affect the reliability. We also recommend that CTA allocate more running time during the PM Peak Westbound and less time Eastbound. After 18:15, we recommend that CTA allocate less running time Westbound and more time Eastbound.

Section 3.2.2 showed that operators take very little recovery time at 92 Buf and usually prefer to layover at 92 Com traveling Westbound. They also appear to kill time en route, particularly on the last segment of the route Eastbound and on the first segment of the route Westbound. Consequently, CTA should consider allowing recovery at 92 Com where there is a nice business district instead of 92 Buf which is not a safe and comfortable place to take a break. This could encourage more uniform operator behavior similar to that at the Western terminal and therefore decrease the headway variability Westbound.

6.2.2. Route 85 Recommendations

As with Route 95E, one of the causes of unreliable service on Route 85 appears to be operator behavior and the lack of consistent schedule-based holding. This leads to headway variability which triggers unreliability for waiting passengers and longer in-vehicle travel time for onboard passengers. We recommend that CTA also reinforce the schedule-based holding strategy on Route 85.

Reducing the running time scheduled on segments would encourage operators to hold when necessary. We observed that too much running time was scheduled on most route segments. When the running time scheduled on many route segments allows more than 75% of vehicles (and even 100% of vehicles on NorCen-FulCen!) to complete the segment within the scheduled segment time, operators become frustrated by continually having to hold for long durations. Consequently, they either kill time en route or hold longer at a prior time point in order to not hold too long at the following time points. It is even more frustrating to operators when time points are situated very close to each other on the route; on average time points are situated one mile apart on Route 85. It is difficult to require operators to hold for a few minutes each mile. This is especially true since the number of waiting passengers is greater than the number of through passengers on this route. For the same reasons, we advise CTA to eliminate time point JpkB12, which is the same physical point as JpkBlu and is used only to hold operators.

We also recommend that CTA implement more uniform headways during each time period on this route since the current practice of varying consecutive headways may well lead to bus bunching. This issue may be related to the fact that CTA wants to save resources and consequently must pull buses on and off the route at various points within a time period. To improve the reliability of route 85, the CTA should attempt to schedule a more uniform headway within each time period.

6.2.3. General Recommendations

Reliability and passenger service quality can be improved by enforcing schedule-based holding, which is critical to reduce running time variability and consequently headway variability. However, the enforcement of such a strategy may be difficult if too much running time is scheduled on segments and operators have to hold frequently for long durations. This also may result in significant delays for through passengers. To avoid this, we advise implementing a schedule obtained with the generalized cost minimization approach, which would allocate holds only when necessary. Compared with the 65th or 50th percentile running time schedule, the generalized cost minimization schedule results in fewer holds and always reduces the overall costs for passengers, improving reliability and passenger service quality. The magnitude of the benefits will depend on the characteristics of the route. The generalized cost minimization approach will avoid frustration to operators as well as to through passengers.

6.3. Future Research

This research outlined and demonstrated the key points to designing a reliable schedule on high-frequency bus routes. Future research may seek to extend the scope of the model's application and so improve bus service reliability for a wider range of bus routes.

6.3.1. Extensions to the model

a) Revisions of the hypotheses on which the model is built

The model used in the thesis hypothized that consecutive bus vehicle trips are independent and consecutive segment running times for a particular bus trip are independent. The model was directly applicable to Routes 95E and 85 which satisfy these two hypotheses. However, these hypotheses are unlikely to be true in all cases. Consequently, the conclusions of this research can be applied with confidence to routes which satisfy these two hypotheses. Tests similar to those conducted in Chapter 2 can be performed for the routes of interest to verify whether they meet these two critical hypotheses.

If the first hypothesis is not satisfied for a particular route (for example, if the route is a heavy demand route where the headway variability affects the segment running time), the expression for the arrival time at time point i of trip t will have to be modified. Indeed, the running time on the segment, $T_{i,t}$, will be a function of the headway with the preceding vehicle at time point i. The running time on the segment will follow the running time distribution obtained from the AVL data shifted by a value which depends on the headway with the preceding vehicle. In addition the running time distributions estimated from the AVL data will need to be modified to account for the dependency on the headway. This should result in a tighter running time distribution than the ones estimated in Chapter 2 of this thesis for routes which violate this hypothesis.

The same logic applies if the second hypothesis is not satisified, i.e., if consecutive segment running times are correlated. Here again, the segment running time, $T_{i,t}$, will be a random variable rawn from the running time distribution obtained from the AVL data shifted by a value which depends on the running time of the previous segment. Once again this would require re-estimation of the running time distribution with the AVL data to account for this dependency.

The relationships between headway and segment running time or between consecutive segment running times could be obtained from additional analysis of the AVL data.

b) Implementation of the model's approach

Revising the model to make it easy to apply to any bus route would be essential if it is to be usable in practice. A great deal of data processing is needed to generate the model inputs from AVL and APC data. For the analyses presented in this thesis, the data have been processed separately and then input into the model. For more extensive applications, software would have to be developed to automate the data processing as well as the generalized cost minimization method itself.

The schedule obtained with the generalized cost minimization approach will always improve passenger service reliability and quality compared to traditional approaches. The amount of passenger time saved will depend on the characteristics of the route. Therefore, revising the modeling process to make it easy to implement and to use for any bus route would be a significant enhancement. If the model was modified to automatically consider an extensive set of feasible schedules, then evaluate the respective passenger costs and choose the schedule which minimizes the total weighted passenger cost, it would greatly improve its utility.

c) Feasibility of the schedule

The scheduled segment running times obtained with the generalized cost minimization approach are sometimes unreasonable for operators; the approach is the same as suppressing the time point and setting unrealistic trip schedules. To mitigate this issue, a transit agency could modify the model by implementing a percentile running time threshold under which the schedule cannot be set. For example, if the model proposed a low percentile running time on some segments, it would instead return the lower bound specified by the transit agency. The 50^{th} percentile would be a reasonable lower bound for such a time point schedule. Conversely, the transit agency could also use the model as a means to determine which time points are necessary and which could be dropped without a negative impact on the overall reliability of the route.

The outcome for a segment could then be one of the following three possibilities:

- no time point
- the 50^{th} percentile schedule
- a schedule between the 50^{th} and 100^{th} percentiles, as recommended by the model

6.3.2. Demand elasticity

The model presented in the thesis predicts the passenger time saved with different scheduling approaches. It would be interesting to add a demand forecasting model to the current model in order to predict increased ridership due to an improved schedule. An economic study should be performed in order to define the elasticity of demand. In the case of a significant increase in ridership, the scheduler should evaluate a new schedule by changing the frequency of service and possibly, also, the segments' scheduled running times.

6.3.3. Simulation model

Different scheduling approaches were tested with a simple model which uses the current segment running time distributions. Future work might seek to use a simulation model combined with a cost model to examine interesting scenarios in more detail.

6.3.4. Scheduling at the network level

The thesis has shown how to determine a schedule which improves reliability and overall passenger service quality at the route level. Schedule design at the route level places emphasis on detailed descriptions of the stochastic nature of routes, on reliability and on control strategies. As noted by Liu [18], schedule design at the network level deals with problems such as interlining, schedule synchronization, transfers between routes, crew scheduling, deadhead reduction, etc. Ideally, schedule design should begin at the network level and then be followed by a more detailed design at the route level. Therefore, it would be beneficial to have further research on the network level to see if the findings presented here apply to the network interaction issues.

6.3.5. Operator behavior

Operator behavior was not included in the model and was assumed perfect. However, we know that operator behavior influences the variability of the headway. Operators often control their speed on segments of the route in order not to hold at time points. Thus, studying the influence of the scheduled time on operator behavior would be a fruitful area of future research. It would be equally interesting to find the means to alter operator behavior in order to better enforce the schedule-based holding strategy, thereby greatly increasing reliability for waiting passengers.

Reference

[1] Abkowitz, M., H. Slavin, R. Waksman, L. Englisher and N. Wilson (1978). *Transit Service Reliability*. Report No. UMTA-MA-06-0049-78-1. U.S. Department of Transportation

[2] Abkowitz, M and I. Engelstein (1983). Factors Affecting Running Time on Transit Routes, *Transportation Research Record*, Vol. 17A, No.2, pp. 107-113

[3] Abkowitz, M. and I. Engelstein (1984). Methods for Maintaining Transit Service Regularity, *Transportation Research Record*, No. 961, pp. 1-8

[4] Abkowitz, M., A. Eiger, and I. Engelstein (1986). Optimal Control of Headway Variation on Transit Routes, *Journal of Advanced Transportation*, Vol. 20, No. 1, pp. 73-88.

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

[6] Barnett, A. (1978). Control Strategies for Transport Systems with Non-Linear Waiting Costs, *Transportation Science*, Vo. 12, No. 2, pp. 119-136

[7] Bly, P.H. and R.L. Jackson (1974). *Evaluation of Bus Control Strategies by Simulation*, TRRL Laboratory, Report No. 637, Crowthorne (Great Britain)

[8] Bursaux, D.O. (1979). *Some Issues in Transit Reliability*, unpublished M.S. thesis, Department of Civil Engineering, Massachusetts Institute of Technology

[9] Cham, L., (2006), Understanding Bus Service Reliability: A Practical Framework Using AVL/APC Data. *Masters Thesis: Department of Civil and Environmetal Engineering, Massachusetts Institute of Technology*

[10] Cohen, J. (1988). Statistical power analysis for the behavioral sciences (2nd ed.) Hillsdale, NJ: Lawrence Erlbaum Associates. ISBN 0-8058-0283-5.

[11] Furth, P., Hemily, B., Muller, T., Strathman, J., (2006) Using Archived AVL-APC Data to Improve Transit Performance and Management, *Transit Cooperative Research Program,* Report No. 113

[12] Furth, P. and Muller, T., (2007), Service Reliability and Optimal Running Time Schedules. *Transportation Research*, Paper No. 07 – 2694

[13] Hastus ATP – Training Guide (V2005) – CTA

[14] Holroyd, E.M. and D.A. Scraggs (1966). Waiting Time for Buses in Central London, *Traffic Engineering and Control,* Vol. 8, No. 3, pp. 158-160

[15] Hong, Y., (2002), The Development of More Effective Operating Plans for Bus Services. *Masters Thesis: Department of Civil and Environmental Engineering Massachusetts Institute of Technology*

[16] Kittleson & Associates et. al. *Transit Capacity and Quality of Service Manual*, 2nd ed. TCRP Report 100, 2003.

[17] Koffman, D. (1978). A Simulation Study of Alternative Real-Time Bus Headway Control Stratgies, *Transportation Research Record*, No. 663, pp. 41-46

[18] Liu, G., (1995), Time Points and Schedule Design for a Fixed Transit Route Adopting a Holding Control Strategy. *PhD Thesis: Department of Civil Engineering, The University of Calgary*

[19] Muller, T. and Furth, P., (2001), Trip Time Analyzers: Key to Transit Service Quality, *Transportation Research*, No.1760, pp. 10-19

[20] Multisystems, Inc. (1984). *Bus Transit Monitoring Manual*, U.S. Department of Transportation, Urban Mass. Transportation Administration

[21] Osuna, E.E. and G.F. Newell (1972). Control Strategies for an Idealized Public Transportation System, *Transportation Science*, Vol. 6, pp. 52-72

[22] Transportation Management & Design, INC (September 2003). *CTA Bus Schedules Efficiency Review – Final Report*

[23] Welding, P.I. (1957). The Instability of a Close-Interval Service. *Operational Research Quaterly*, Vol. 8, No. 3, pp. 133-142.

[24] 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.