IMPROVING TRANSIT SERVICE CONNECTIVITY: THE APPLICATION OF OPERATIONS PLANNING AND OPERATIONS CONTROL STRATEGIES

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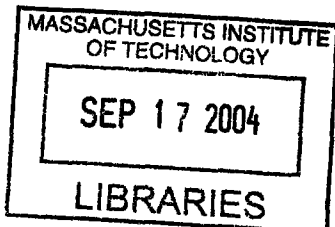
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Abstract

Providing direct public transportation service for every origin-destination pair is very expensive if not infeasible for a transit agency, so it relies on the willingness of passengers to transfer. However, transfers usually reduce the attractiveness of transit because they add uncertainty, discomfort, waiting time and cost to most trips. This research focuses on examining different transfer coordination strategies that can reduce the disutility of transfers by minimizing the expected waiting times of transferring passengers.

Two models are developed to assess scheduling and real-time holding decision rules for vehicles on a transit corridor. The operations planning model involves the simultaneous application of two planning strategies: changing the terminal departure time and inserting slack time. The operations control model has the capability to utilize any available current network information and to determine optimal dispatch times for vehicles at transfer stops.

The two models were tested on a hypothetical corridor to illustrate their applicability in coordinating transfers. On the planning side, results showed that there is a high threshold for introducing slack time to the schedule and that the greatest benefits from schedule coordination are attained when the variance of vehicle arrival times is small and the headway on the analysis corridor is long. On the control side, it was shown that transfer demand is a major driving factor behind any holding recommendation. Moreover, the greatest benefits from real-time coordination occur when the required holding time and the preceding headway of the vehicle on the destination line are short and its following headway is long.

The application of the models to two CTA bus routes: 53 and 63, showed that the benefits accrued from coordinating schedules on Route 53 were not significant mainly due to the headway compatibility requirement which reduces the number of transfers amenable for improvement. Greater benefits were encountered when the schedules on the connecting routes were allowed to change as well. For Route 63, schedule coordination is not worth attempting due to the combination of the short six-minute headway on that route and the high variability in vehicle arrival times. On the control side, the practice currently adopted at CTA is to hold a "ready" vehicle at a transfer stop if the connecting vehicle has already arrived and this is likely to be an effective as well as easy-to-implement control policy.

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TO MY PARENTS
JAMIL AND FATINA

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1   INTRODUCTION

The continuing shift of activities from city centers to other areas is resulting in increasingly dispersed origin-destination patterns. Providing adequate direct transit service between all these origins and destinations is financially infeasible in any public transportation network regardless of the agency size and available resources. That is why most agencies rely on the willingness of their passengers to transfer to complete many of their trips, by connecting to other services (route) at specified transfer stops. Unfortunately, transfers have a number of attributes which make them inconvenient. Among these are the physical effort associated with alighting from one vehicle and boarding a new vehicle, the additional transfer fare, and the negative perception of waiting for the arrival of the destination vehicle. Partly to avoid this transfer inconvenience, many potential transit passengers instead use their private autos.

This thesis will present strategies and develop models which aim at reducing the waiting time of transferring passengers at selected transfer stops along a transit corridor through the application of operations planning and operations control techniques. This chapter addresses the role of transfers in transit networks and introduces the methods used to reduce their disutility. Later sections in the chapter describe the objectives of this research, present the methodology and provide a brief overview of the rest of the thesis.

1.1 TRANSFERS IN A TRANSIT NETWORK

In many large urban transit systems, 10 to 30% of the total daily transit trips include at least one transfer. The Chicago Transit Authority (CTA), which will provide the main case study application for this research, is a case in point where transfers play a critical role in the transit operations. The CTA transit network relies heavily on the ability to transfer between routes and services reliably and conveniently [CTA Service Standards, 2001]. Of all transit trips, 32% involve transfers between a CTA bus and train, 15% involve transfers between vehicles of the same mode, and 8% involve transfers between a CTA service and either the commuter rail (Metra) or commuter bus (Pace) systems [Northwest Research Group, 2002].

Transfers can advantageously influence the transit service characteristics of any network by offering passengers a greater range of travel destinations, improving the transit network operational flexibility and efficiency, and concentrating passenger flows on main routes which usually have better service. An efficient transfer system can thus significantly improve the overall service quality offered by the transit agency, stimulating demand and increasing productivity in the network [Ting, 1997]. On the other hand, transfers also add uncertainty, discomfort, waiting time and cost to most trips, thus discouraging passengers from choosing transit. Connecting between vehicles at a transfer stop sometimes requires passengers to walk long distances or to utilize several stairwells depending on the physical characteristics of the stop. Some might have to wait in unprotected locations, subject to inclement weather and security concerns particularly at night and on weekends. At such locations, transfers may be more stressful since there are fewer people available to increase the sense of security and to provide distractions while waiting for the connecting vehicle.

The uncertainty associated with the transfer experience springs from the unreliability in the connecting vehicle arrival times at the transfer stop. These vehicles arrive and depart from the stop with varying levels of adherence to the schedule. This randomness in arrival time may result in transferring passengers missing their planned connection entirely and hence being forced to wait for the next arriving vehicle on their destination line.

The transfer waiting time –the most inconvenient aspect of transfer – is therefore influenced by the reliability of the connecting routes at the transfer stop. This waiting time is also affected by the frequencies on those routes [Crockett, 2002]. When transferring between high-reliability routes, the waiting times experienced by transferring passengers are known and can be reduced substantially through the application of coordination strategies – introduced in the next section. When connecting between a high-reliability route and a low-reliability one, the transfer waiting times are variable, but long waiting times can be avoided by applying the appropriate strategy. Finally, for transfers between low-reliability routes, the resulting waiting times are very variable and it is often not worth attempting any coordination. Service connections, even if planned, are not possible most of the time. The impacts of the reliability of vehicle arrival times on the transfer waiting time are summarized in Table 1-1.

Table 1-1. Impact of Line Reliability on Transfer Waiting Time (derived from [Crockett, 2002])

From / To	High Reliability	Low Reliability
High Reliability	Waiting time is known	Waiting time is variable
Low Reliability	Waiting time is variable	Waiting time is very variable

The transfer waiting time is also a function of the frequencies on the connecting routes as shown in Table 1-2. Connections are of particular concern when the headways on both routes are long. For such cases, the transfer waiting time can be very long if there is no coordination between the arrival and departure times of the connecting vehicles. On the other hand, when transferring between high-frequency routes, transfer waiting time is a relatively minor concern because there is an expectation that a connecting vehicle will be there shortly. This is also the case when transferring from a low-frequency route to a high-frequency route.

Table 1-2. Impact of Line Frequency on Transfer Waiting Time (derived from [Crockett, 2002])

From / To	High Frequency	Low Frequency
High Frequency	Waiting time is always short	Waiting time is variable
Low Frequency	Waiting time is always short	Waiting time is variable

The different aspects of the transfer experience make transfers burdensome and annoying for most passengers, but despite this, transfers can not be avoided. The only alternative is, therefore, to minimize their disutility to transit passengers. In fact, improving the transfer experience has become a growing concern for many agencies due to its significant impact on the passengers' perception of the overall quality of transit service and hence on the agency's total ridership and revenue. Transit agencies expect that better transfers should result in travel experiences which are more satisfying to the customer and which should eventually translate into increased ridership.

1.2 Improving the Transfer Experience

There is a wide range of improvements that can be made to the typical transfer experience. If the connecting vehicles arrive and depart with more certainty, the transfer waiting time is minimized, the conditions of the transfer are made more favorable, or the cost of a transfer is eliminated, then the disutility of a transfer can be reduced. This thesis focuses on the strategies that minimize the transfer waiting time, which is the primary driver of customer satisfaction. This time is considered "wasted" from the perspective of the passengers. In fact, the minimization of transfer waiting time is a primary concern at CTA particularly since this transfer attribute has been given a D grade among the areas that require improvements [Northwest Research Group, 2002].

Crockett [2002] analyzed the three different elements that affect every transfer - system, facility, and service elements – and explored the development of guidelines and standards around these elements leading to cost-effective improvement strategies. On the service side, she proposed modifications to the scheduling process that would reduce the waiting time for many transferring passengers, especially those connecting to lower frequency routes. She concluded that if the connecting lines have matched headways and slack times introduced to their schedules at the transfer stops, then the opportunities for shorter transfer waiting times can be increased. At CTA, the schedules of different lines are generally not coordinated, which increases transfer waiting times. Modifying arrival and departure times from a transfer stop has the potential to reduce the waiting times of transferring passengers by a significant amount. She also suggested that CTA standardize its headways in the off-peak period making them ten, twenty, or thirty minutes to make it easier to coordinate transfers.

In general, transfer waiting time can be improved through the implementation of either schedule coordination or real-time coordination or some combination thereof. Schedule coordination involves modifying the current service timetables in order to minimize the overall passenger waiting time in the network and to improve its transfer performance. Three strategies are applied in practice: changing the terminal departure time of the vehicles on the connecting routes, adding slack time to the schedule of the different routes, and adjusting the service frequencies. However, no operation strictly conforms to the operations plan. Because of the inherent stochasticity in a transit network, simply synchronizing scheduled vehicle arrivals among connecting routes at transfer stops is unlikely to significantly reduce transfer waiting time. When disruptions occur, real-time control systems utilizing any available current network information

(i.e. vehicle locations and passenger loads based on ITS technologies) can determine dispatch times for vehicles at transfer stops in a dynamic way to optimize the transfer performance. (A detailed discussion of the operations planning and control strategies is presented in Chapter 2).

It should be noted that transfer coordination schemes are easier to implement and are expected to yield more benefits in a network where all the routes connect at one transfer stop. In such a network, vehicles can be scheduled to arrive and depart from the stop in a way that allows for the maximum number of convenient transfers. As the number of transfer stops increases, the implementation of transfer coordination strategies becomes more difficult. A schedule which produces good transfer connections at certain stops may produce poor connections at others. For instance, consider a network where three transit routes connect at three transfer stops. If the arrival/departure times of the routes are coordinated at two of the transfer stops, then the transfer conditions at the third stop are predetermined and may lead to conflicts at this stop [Ting, 1997]. Therefore, as the network geometry becomes more complex, the interaction among all the transfer stops must be considered in scheduling. Consequently, transfer coordination initiatives might not be as efficient.

1.3 RESEARCH FOCUS AND OBJECTIVES

This research focuses on developing an operations planning and an operations control model which can be applied to any corridor in a transit network. The purpose is to recommend scheduling and real-time holding decision rules for the vehicles on that corridor in order to improve the transfer performance at selected transfer stops.

The objectives of this research are, therefore:

1. To develop a better understanding of the different strategies which can be used in practice to coordinate transfers;

2. To develop two computer models – an operations planning and an operations control one – that can be used to identify strategies to improve connectivity on a corridor with multiple transfer stops;

3. To test the applicability of these models in coordinating transfers and to determine the conditions under which each strategy results in the greatest benefits;

4. To apply the models to two CTA bus routes: 53 and 63.

1.4 RESEARCH APPROACH

Transfer coordination can be studied at three different levels: the single stop level, the corridor level or the full network level. It might be most valuable to study coordination at the single stop level in small transit systems where the number of transfer stops is limited to one or a few centralized ones, which act as hubs for a large number of connecting routes. In such systems, timed transfers are usually adopted as a form of coordination whereby the departure times of the different connecting routes from each transfer stop are synchronized to minimize the expected waiting time of transferring passengers. However, such systems are not representative of large cities with decentralized transfers i.e. where transfers occur at virtually every intersection between two routes. Analyzing and applying transfer coordination at the single stop level in large transit networks is not effective because the impacts of any adopted strategy are restricted to one stop only. The transfer performance of the stop in question might be improved significantly, but at the same time, the performance of a number of other stops in the network might be worsened.

This is why in large transit systems, a full network level approach is preferable since the impacts of any strategy should be evaluated for all the stops. However, a network level approach requires a large amount of data that need to be analyzed resulting in a fairly complex transfer coordination problem. In this research, transfer coordination is studied at the corridor level which provides a middle ground since it is not very complex and yet it accounts for the impacts of any adopted strategy at all the stops along the analysis corridor. Moreover, we hope that understanding coordination at the corridor level will provide insights to understanding it at the full network level, which is ideally what every transit agency aspires to.

The first step in the adopted approach involves an extensive literature review addressing the different strategies that are used in practice to coordinate transfers and minimize their negative impacts. Transfer coordination initiatives are divided into two categories: operations planning and operations control. Among the operations planning strategies are changing the terminal departure time, inserting slack time and adjusting service frequencies. The operations control strategy, most widely used in practice, is holding a vehicle at a transfer stop to allow connecting passengers to transfer. The conditions under which each strategy has proven most effective are reviewed and the impacts of each strategy's utilization are presented.

Two computer models are then developed. The operations planning model aims at coordinating transfers at selected transfer stops along a transit corridor so as to improve the overall experience for passengers. This is carried out by recommending a new schedule which minimizes the total expected waiting time of all impacted passengers along that corridor. The operations control model is developed separately from the planning one. The aim of the model is to determine whether holding a vehicle at a transfer stop for an incoming connecting vehicle is appropriate. Such a holding decision is based on the tradeoff between the benefits for transferring passengers and the potentially negative impacts on other passengers at, and downstream of, the transfer stop.

The two models are then tested on a hypothetical corridor to illustrate their applicability in coordinating transfers. The sensitivity of the decision variables and the model results to factors including headways, bus arrival time variance, transfer volumes and passenger time values is also explored. These results will determine the conditions under which each strategy produces the greatest benefits. The results will also help service planners and field supervisors in any agency make informed decisions when faced with similar conditions. Finally, the two models are applied to two bus routes in the Chicago Transit Authority: Routes 63 and 53. The purpose is to assess the potential for new service timetables and real-time holding decision rules to improve the transfer performance on both corridors.

1.5 THESIS ORGANIZATION

This thesis is divided into six chapters. Chapter 2 will discuss the different operations planning and operations control strategies including the results of prior research on this topic. Chapter 3 will present the principles, assumptions and structure behind the development of the two computer models. Chapter 4 will test the applicability of these models on a hypothetical corridor and will study the sensitivity of the results to changes in the corridor characteristics. Chapter 5 will apply the operations planning and operations control models to two corridors at CTA. Finally, Chapter 6 will summarize the findings of the research, present recommendations, and suggest areas for future research.

2   TRANSFER COORDINATION STRATEGIES

Many strategies have been implemented by transit agencies to reduce the negative impact of transfers. A fair amount of work has also been published on different analytical and simulation models which were designed with this objective in mind. This chapter presents the different strategies aimed at improving the transfer experience of transit riders by minimizing their overall transfer waiting time. The general cost structure used in the evaluation of the effectiveness of each strategy is first introduced. The various operations planning and operations control techniques are then explored; the conditions under which each strategy has proven most effective are reviewed and the impacts of each strategy are presented.

2.1   COST STRUCTURE

A general cost structure used in the evaluation of the effectiveness of each strategy is first introduced. Ting [1997] defined this cost function as the difference between the costs of the coordinated and uncoordinated network operations. The cost structure for such operations is shown in Figure 2-1. Both types of operations include transfer and non-transfer costs. The non-transfer cost includes vehicle operating cost, passenger out-of-vehicle cost and passenger in-vehicle cost. Transfer cost for the uncoordinated operation includes the missed connection cost which is incurred by transferring passengers when their connection is unsuccessful. These passengers now have to wait for the next arriving vehicle on the line they are transferring to. Transfer cost for the coordinated operation includes either the missed connection cost or the delay cost. The latter occurs when a successful connection takes place. In this case, non-transferring passengers might experience in-vehicle delay, the transit agency might suffer extra costs in the form of additional vehicle-hours and sometimes even additional vehicles, and transferring passengers might experience some delay (out-of-vehicle and/or in-vehicle) depending on the joint arrival time distributions of both connecting vehicles. While the cost components for the uncoordinated operation remain unchanged for a given network, those for the coordinated operation vary depending on the strategy used. The best transfer coordination strategy results in the minimum value for the sum of the coordinated cost components. In other words, it results in the maximum difference between the costs of the coordinated and

uncoordinated network operations and hence in the maximum value for the total system cost function. In this chapter, the discussion of the different cost components will be limited to the coordinated operation while considering the uncoordinated operation as the base case against which each strategy is compared.

Figure 2-1. Cost Structure (derived from [Ting, 1997])
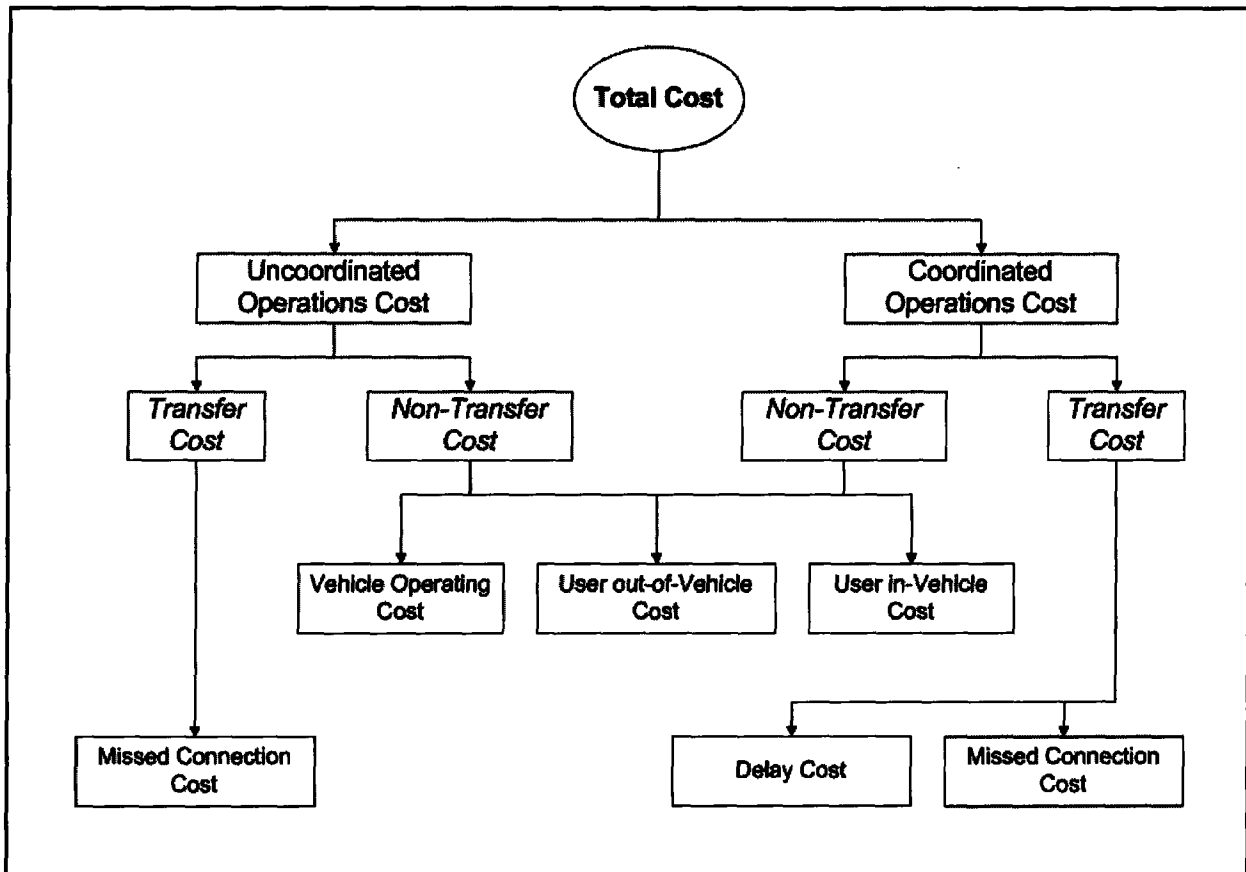
Each of these coordinated operations can be represented by a decision variable that enters into the definitions of the different cost components. The various analytical and simulation models, which have been researched over the last decade and a half, have concentrated on finding optimal values for the decision variables that result in the minimum total cost for each strategy. These optimal values lead to network operations where the expected benefits of transferring passengers are maximized and the costs to both non-transferring passengers and the transit agency are minimized.

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2.2 OPERATIONS PLANNING STRATEGIES

The first set of strategies is applied during the operations planning process. This process involves a sequential approach whose main stages are designing the network, setting service frequency and service span, developing the timetable, scheduling vehicles and finally scheduling crews. While ideally all these components would be planned simultaneously to utilize the network's capability to the greatest extent and to maximize its productivity and efficiency, such a simultaneous process is extremely complex. The operations planning process therefore seems to require separate treatment of each component, with the outcome of one becoming an input to the next [Ceder, 1986]. The analysis presented in this thesis assumes the first stage as given. In other words, each strategy considers a predetermined network of transit routes and changes a particular schedule parameter to improve the overall performance of the network. Three operations planning strategies are discussed in this chapter: changing the terminal departure time, inserting slack time and adjusting service frequency.

2.2.1 Changing Terminal Departure Time

This technique aims at developing a better timetable for the connecting routes of a network. It aims to reschedule the departure times of vehicles from their respective terminals so that they will arrive at the various transfer locations at approximately the same time in order to allow for successful connections and hence minimize the aggregate transfer delays systemwide. The adopted approach is usually an iterative one which starts with the current timetable and then changes the schedule of one line at a time until no further improvement can be obtained. The line definition in this analysis is directional; a line is a portion of the route that proceeds from one terminal to the other. The output from such a strategy is a timetable for each line described by a vehicle's departure time from the terminal along with the predefined sequence of headways between consecutive trips.

The concept of transfer optimization, another term for this strategy, appeared for the first time in a paper by Rapp and Gehner [1976]. The paper describes an operational tool that minimizes transfer delays through an automated iterative analysis of terminal departure times as part of a computerized transit planning system. In 1977, Volvo developed a different transit planning software package including a similar transfer optimization option [Andréasson, 1977]. Both tools assume that the transit network is in a steady state over the time period to be optimized. The inputs to these tools therefore include a predetermined set of headways, fixed demands for lines

and transfer connections, and constant bus travel times. The objective function used in the evaluation is the total waiting time for passengers transferring during the period of analysis. A heuristic technique then searches all the possible terminal offset time combinations of the different lines and selects the set which minimizes the transfer waiting time.

Keudel [1988] described a system which applies a traffic light synchronization algorithm to the problem of optimizing transfers. Two points are of interest in this algorithm. First, the model deals explicitly with the randomness in bus travel times. Second, the algorithm uses an objective function which minimizes both the total transfer waiting time along a corridor and the number of waiting times exceeding a certain value. Klemt and Stemme [1988] formulated a model in terms of both graph theory and integer programming concepts. Each route in the network was assigned a set of nodes corresponding to its permissible departure times. Nodes for connecting routes were linked by arcs with the value of each arc equal to the associated transfer cost. The optimal timetable was then determined by the subgraph that contained exactly one node from each route with the minimum sum of arc values between these nodes.

Most of the literature discussed so far on this strategy did not deal effectively with the issue of randomness of bus travel times although it is a major cause of inconvenience for transfers. The developed models, except for Keudel's, either assume travel times to be deterministic or do not explain explicitly how randomness is taken into account. Bookbinder and Desilets [1992] showed the importance of considering randomness of bus travel times when optimizing transfers in a transit network. A shifted truncated exponential distribution was used to account for stochasticity in travel times. This distribution assumes that the bus arrival times on the feeder line have values in a finite interval with a lower limit equal to the earliest possible arrival time and an arrival spread less than half the headway of the receiving line. In addition to the previous assumptions concerning the steady state of the network during the period of analysis, the paper considered transfers to be strictly from the feeder line to the receiving line. The analysis was carried out for both a single transfer connection and a complete network through a combination of simulation and optimization. The first objective function used was the total waiting time which penalizes long and short transfer waiting times with the same weight and does not take into account the reliability of the transfer connection. To account for such factors, Bookbinder and Desilets also studied other disutility functions such as the square of the waiting time and its variance. Results showed that optimizing a transfer connection under the assumption of deterministic travel times usually leads to poor performance. The negative consequences of such an assumption, however, get smaller when optimizing many connections in a large

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network since the optimal and worst timetables do not produce optimal and worst conditions for every connection. Bookbinder and Desilets also concluded that transfer optimization would produce the most improvement over a randomly selected timetable in a network with large headways on the receiving lines, small arrival spreads on the feeder lines, and relatively directional transfers.

Each of the previous papers presented a different model specification for the transfer optimization problem. However, all these models attempt to find optimal values of the same set of decision variables: the departure times from the terminals of the first bus on each line in the transit network during the time period considered. This optimal set of offset times describes an optimal timetable which leads to a minimum value for the coordinated operations cost function, the structure of which was presented in the first section of this chapter. The operating cost of the transit agency does not change as a result of this improvement strategy which is determined by the headways and the cycle times of each line. Consequently, the number of vehicles operating in the network and the number of vehicle-hours remain the same as in the uncoordinated operation. The passengers' in-vehicle and out-of-vehicle non-transfer costs are also unaffected by the timetable. The only cost component that changes is the transfer waiting time for transferring passengers. These passengers benefit from this improvement strategy since they now generally experience shorter expected transfer waiting times. Adding all these cost components, the cost obtained from this coordinated operation is smaller than that obtained from the uncoordinated one unless the current timetable happens to be optimal.

2.2.2   Inserting Slack Time

An alternative scheduling strategy also aims at developing timetables for different connecting lines so that particular trips might meet at certain transfer locations within given time windows. Slack time is usually added to the schedule at these transfer locations to ensure that smooth connections occur even if some of the trips are late. As shown in Figure 2-2, this slack time can be defined as the difference between the scheduled departure time of a bus from a transfer stop and its expected arrival time at that stop. The addition of this slack time is meant to increase transfer reliability by absorbing some of the service randomness and hence reducing the probability of missed connections.

Figure 2-2. Slack Time Definition (derived from [Wirasinghe and Liu, 1995])
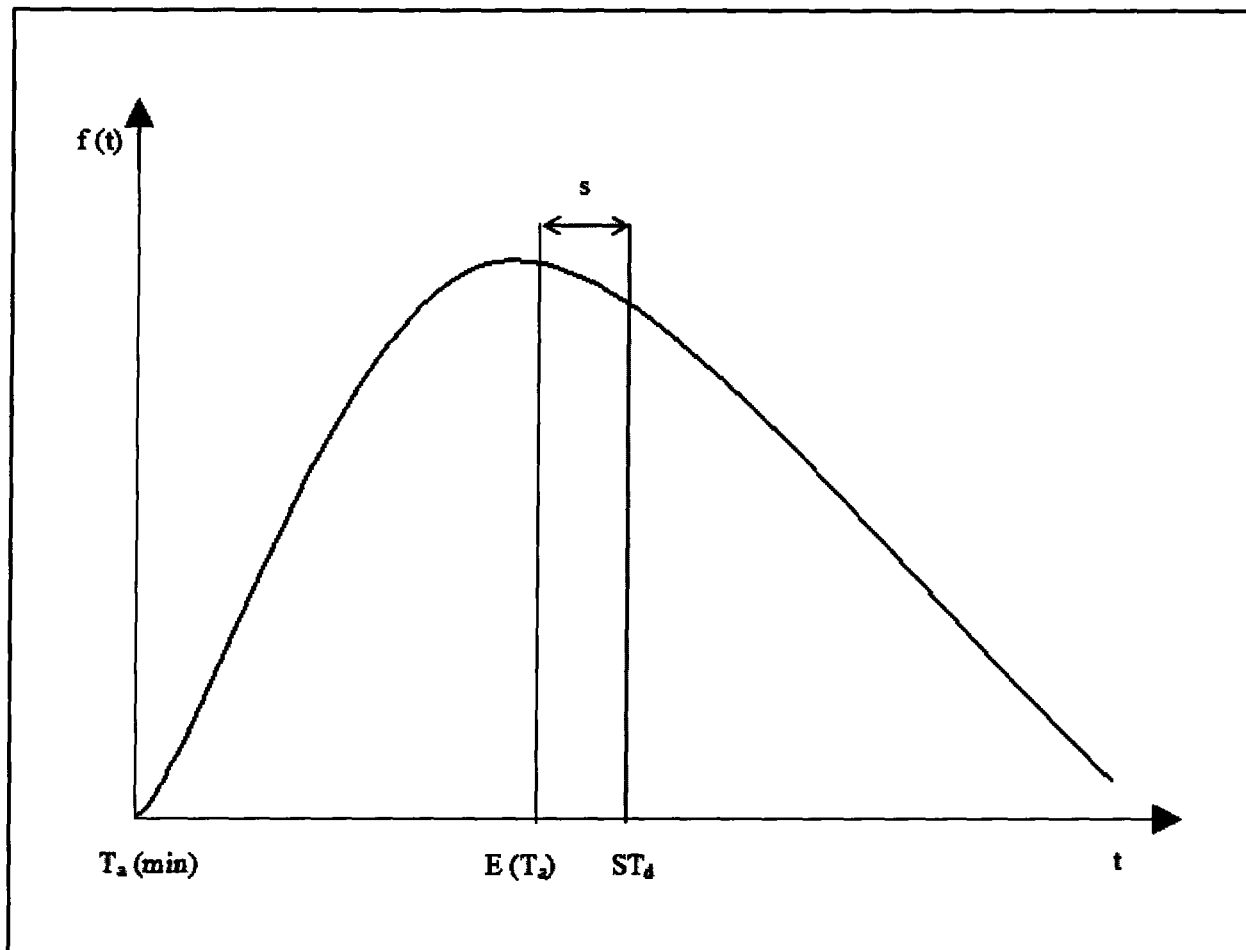
Where,

T_a (min) = minimum arrival time

$E(T_a)$ = expected arrival time

ST_d = scheduled departure time

s = slack time

Under this schedule, a vehicle ready to depart from a transfer stop at a time earlier than the scheduled departure time will be held until the scheduled departure time. However, if it is delayed beyond the scheduled departure time, it will depart immediately upon completion of passenger processing [Wirasinghe and Liu, 1995]. This relationship between arrival time and departure time is depicted in Figure 2-3 below.

Figure 2-3. Arrival Time and Departure Time Relationship [Wirasinghe and Liu, 1995]
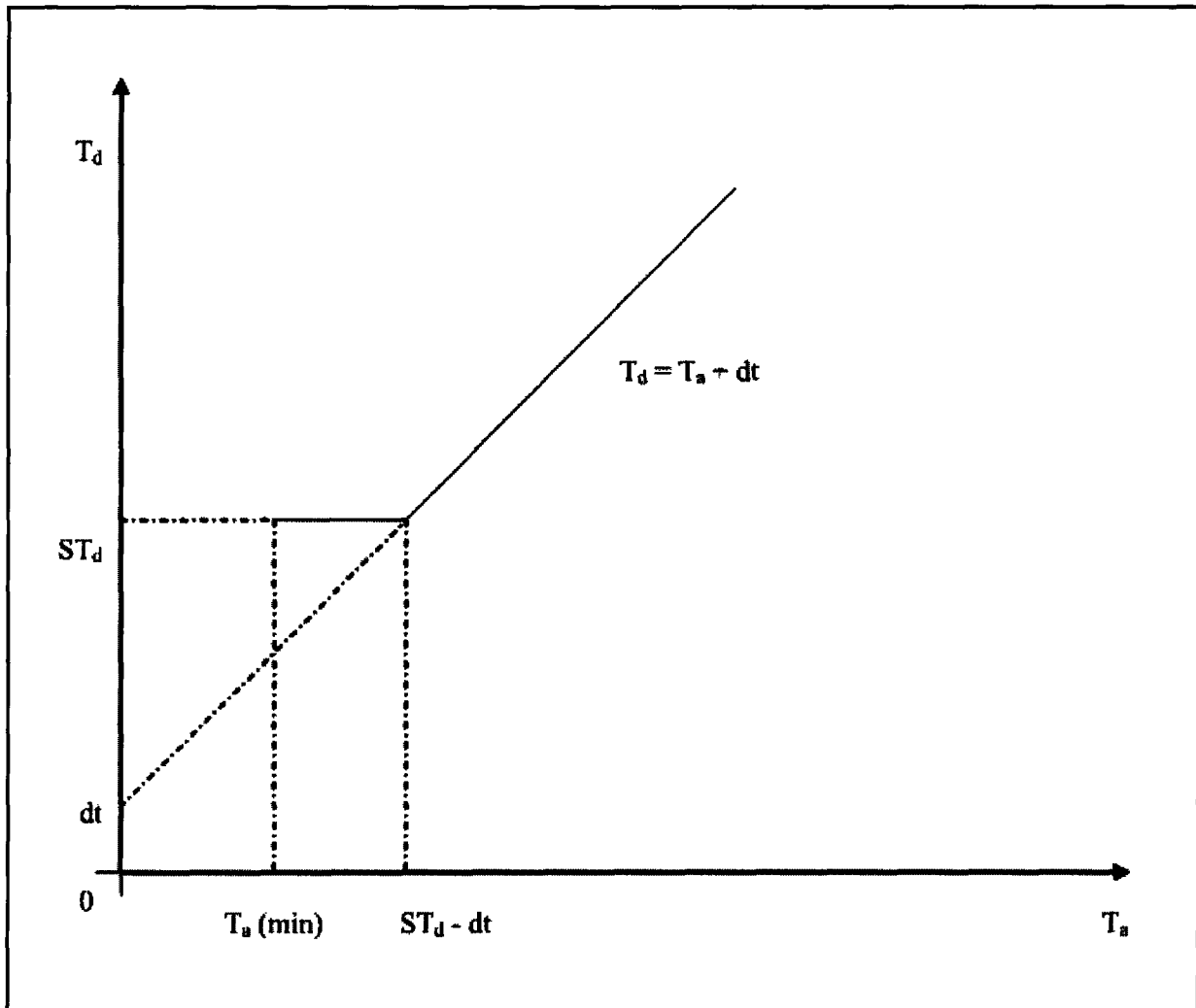
Where,

T_a (min) = minimum arrival time

T_a = actual arrival time

T_d = actual departure time

ST_d = scheduled departure time

dt = dwell time

A large number of analytical studies have been undertaken to optimize slack times at transfer points. Hall [1985] examined transfers to and from a rail line at a transportation terminal and developed an analytical model to minimize the expected passenger delays at that terminal assuming that vehicles are randomly delayed en route. Equations for this expected delay were established based on the average vehicle delay, the headway on the transfer line, and the slack

time. Hall's model has some weaknesses, however, including the use of exponential distributions for vehicle delays and the neglect of costs in the objective function which simply minimizes wait time for transferring passengers. Hall showed that coordinating arrivals with departures is most valuable when the headway on the transfer line is large relative to the expected vehicle delay on the delivery line. Hall also showed that passenger delay becomes more sensitive to slack time as the headway increases and the expected vehicle delay decreases.

Lee and Schonfeld [1991] also formulated an analytical model incorporating stochastic bus vehicle arrivals to determine the optimal slack time needed in the schedule at a transfer terminal connecting a bus route and a rail line. The objective function includes three different cost types: scheduled delay cost of buses and passengers, missed connection cost of bus passengers transferring to rail, and missed connection cost of rail passengers transferring to bus. The sensitivity of this optimal slack time to various factors such as headways, passenger values of time, bus operating costs, standard deviations of bus arrival times, and relative transfer volumes was also explored. Results showed that the standard deviation of arrival time is an important factor affecting the optimal slack time. As this standard deviation increases, the slack time initially increases but then declines, eventually to zero. Beyond a certain level of randomness, represented by critical values of the standard deviation, coordination of connecting routes is not worth attempting. Conversely, coordination is most feasible and desirable when arrival time uncertainties are low. Results also showed that the optimal slack time is zero when the headway on the transfer line is small, and it increases at a decreasing rate beyond a certain critical headway.

Wirasinghe and Liu [1995] designed an optimal schedule for a simple bus route consisting of only two links and one intermediate stop which serves as a time point. The basic decision as to the amount of slack time that should be inserted in the schedule at this time point was investigated using a total cost function which includes the passenger waiting time cost, delay cost to through passengers, delay/early penalty and the agency's operating cost. It was shown that the optimal design of a schedule is very sensitive to the passenger demand patterns along the route.

Knoppers and Muller [1995] investigated the impact of stochastic vehicle arrival times on the passengers' transfer wait time. They showed that coordination – in the form of adding safety margins to the schedule – is worthwhile only when the arrival time standard deviation on the

feeder line at the transfer stop is less than 40% of the headway on the pick-up line. In all other cases, the potential yield from such schedule coordination is small.

Ting [1997] formulated a total cost function to assess the effectiveness of coordinated operations under various demand and arrival time distributions. This function was expressed in terms of weighted operator and user costs and was developed for three different scenarios: uncoordinated operation, fully-coordinated operation and partially-coordinated operation. Two heuristic algorithms were then employed to find values for headways and slack times which minimize this cost function for each scenario. The sensitivity of optimal slack times to variables such as headways, vehicle arrival time variances, transfer volumes and passenger time values was also explored. Results showed that as the headway increases, coordinated operation becomes more desirable and the optimal slack time increases at a decreasing rate as shown by Lee and Schonfeld [1991].

Chowdhury and Chien [2001] studied transfer coordination by optimizing headways and slack times for coordinated lines in an intermodal transit system consisting of a rail transit route and a number of feeder bus routes connecting at different transfer stations . Results showed that coordination is desirable under conditions of low through-passenger demand and long headways. They found that coordination reduced the transfer costs and operator costs, while the wait and in-vehicle costs were increased. However, the savings in transfer cost compensated for the increase in wait and in-vehicle costs resulting in a significant reduction in total passenger costs for such an intermodal transit network.

Cardone et al. [2002] developed a model that was used to optimize a non-stop feeder bus service from the Red Bank Train Station to Sandy Hook Park, Monmouth County, New Jersey. This model minimized a total cost function comprising both passenger and operator costs. The decision variables including headway, fleet size, vehicle size and slack time were jointly optimized analytically under the assumption of time-varying demand.

All the above studies arrive at one common conclusion. Considerable passenger transfer wait time may be saved at transfer stops if the vehicle arrivals from the different lines are coordinated. Since vehicle arrival times are usually stochastic, safety factors – called slack times - are built into the vehicles' schedules at these transfer stops to help reduce the probability of missed connections and therefore reduce the expected transfer wait times. The

feasibility and desirability of such a strategy, however, depends on a number of factors including the arrival time variance, the headways, and the transfer demand.

Adding slack time is usually desirable at transfer stops with high transfer demand from a delivery line with small service randomness to a pick-up line with low service frequency. Bookbinder and Desilets [1992] also argued that this strategy is inappropriate for large transit networks with dispersed transfers; it is mostly desirable in a medium-density community where most of the routes meet at a few designated transfer locations that act as hubs or transfer centers. Adding slack time to the schedule at those hubs may improve transfer reliability and reduce the transfer waiting times. However, these slack times impose higher operating costs on the transit agency and delays for non-transferring passengers. That is why decisions concerning the amount of slack time to be added at a particular stop should be made recognizing the tradeoffs among the various cost components associated with the schedule at that stop. The addition of slack time to the schedule increases the operator cost since the half cycle time of that line now increases implying additional vehicle hours and, in some instances, additional vehicles to maintain the same level of service. This added time also imposes delays on through passengers who are now delayed on the vehicle for the duration of the slack. No effect should be noticeable on other non-transferring passengers, such as those boarding the held vehicle at the transfer stop, since these are assumed to adjust to the revised timetable. Only the transferring passengers are positively influenced by this strategy since they now experience shorter expected transfer wait times given that they make the connection. In the event that the pick-up vehicle departs before the transferring passengers make their connection, the total "coordinated" operations cost will clearly be greater than the total "uncoordinated" operations cost since all the parties involved experience delays.

2.2.3 Adjusting Service Frequency

The third and final operations planning strategy to minimize transfer inconvenience involves changing the headways of some (or all) of the lines connecting at a particular transfer stop so as to minimize passenger transfer time. This approach impacts not only the transfer cost but also the non-transfer cost in the total coordinated operations cost function. Decreasing the headway on the receiving line, for instance, reduces transfer wait time and also implies shorter wait time for those passengers boarding that line. However, such a tactic usually implies added cost to the transit agency since it involves increasing the number of vehicles scheduled on that line. In

most cases, the added cost to the agency can not be justified by the increase in customer satisfaction and the savings in wait time.

Given budgetary and/or fleet size constraints, some agencies may reduce service on some routes to coordinate headways with connecting routes. As long as the agency's service standards are still met, increasing headways may be acceptable. This approach is justified only if the added cost to non-transferring passengers – in the form of additional wait time – is outweighed by the benefits accrued by transferring passengers and the transit agency. Crockett [2001] suggested an alternative service plan for Tren Urbano, the new rail rapid transit system for the San Juan Metropolitan Area, which would increase rail headway from four to five minutes. Her main argument was that the headways of both the rail system and the feeder bus system should be matched to derive the greatest benefits. Since the number of buses and their operating budget are limited, it would be harder to match the bus system to the 4-minute headway of the initial Tren Urbano contract service plan without eliminating some of the routes. Hence, it would be easier to increase the train headways in order to match them with those of the bus ensuring connectivity between the rail system and the feeder bus system, minimizing the transferring passengers' wait time, and at the same time evening out the load on the buses to avoid crowding and bunching.

The planning software package developed by Volvo [Andréasson, 1977] also determines frequencies of given routes so that passenger transfer waiting time is minimized. The algorithm used starts from minimum frequency on each route and improves until a resource limit is reached or until further improvements cost more than they are worth in terms of passenger time savings. If different vehicle sizes are available for each route, the choice of vehicle type is also optimized.

Ceder et al. [2001] addressed the problem of generating a timetable for a given network of buses by optimizing the different line headways while maintaining the available fleet size on each line. A mathematical model was formulated as a mixed integer linear programming problem and a heuristic algorithm was developed to solve it in polynomial time. Preset minimum and maximum values for the different line headways, the number of hourly scheduled departures for each line, and deterministic link travel times were used to determine the headways on each line which maximize the number of simultaneous bus arrivals at the transfer stops of the network and hence enable the transfer of passengers from one line to another with no wait time at those stops. One of the main weaknesses of this model, however, was the

assumption of deterministic travel times. As was shown in the previous two transfer coordination strategies, the variance of the vehicles' arrival times is a very important factor in the success (or failure) of any strategy and should therefore be taken into account when developing any model.

While adjusting service frequencies may sometimes be feasible, it is seldom a desirable strategy in practice.

2.3 OPERATIONS CONTROL STRATEGIES

Minimization of transfer disutility can be achieved by applying either static or dynamic measures. Static measures – as discussed in the previous section – generally involve setting new service timetables, whereas dynamic measures involve real-time adjustments of the operations plan. These operations control measures are usually performed at particular transfer stops where a transit vehicle is held to allow for passenger transfers from incoming feeder vehicle(s). If the transfer stop is a timepoint, holding would occur only if the departure time is delayed beyond the vehicle's scheduled departure time. Otherwise, vehicle holding starts after the conclusion of passenger processing at the stop. In a sense, these control measures are similar to the schedule-based holding strategy whereby slack time – comparable to holding time – is inserted in the schedule at the transfer stop. The main difference, however, is that the departure time of the vehicle under such control measures is not fixed a priori; rather, it depends on the current state of the system, specifically on expected future vehicle arrival times and passenger loads.

Dispatching control strategies have been investigated extensively in the literature. Most studies, however, have dealt with such actions as a measure of optimizing system performance when service disruptions occur. These typically involve actions intended either to return service to schedule for routes characterized by long headways or to restore scheduled headways for routes operating at high frequency. Only a few studies have dealt with control strategies as a means of improving the transfer experience of passengers while minimizing the total system cost, and several of these studies are summarized below.

Abkowitz et al. [1987] developed a computer simulation model to evaluate and compare the service quality improvements attained by applying the following four strategies:

- Unscheduled (also referred to as the do-nothing scenario) – buses are not scheduled to meet at a transfer stop and do not wait for each other.

- Scheduled – buses are scheduled to meet at a transfer stop but do not wait for each other.

- Single holding – buses are scheduled to meet at a transfer stop and the lower frequency bus holds for the next arriving bus on the higher frequency line.

- Double holding – buses are scheduled to meet at a transfer stop and the first arriving bus holds for the next arriving bus from the other line.

The scheduled strategy, which involves only static measures, shows significant improvement over the base scenario when headways are integer multiples of each other. The single holding strategy yields results similar to the scheduled strategy, except that it is more sensitive to the boarding and alighting profiles of the route designated for holding. Finally, the double holding strategy outperforms all the other strategies when the headways on the intersecting lines are equal.

Dessouky et al. [1999] developed a simulation model to test various bus holding strategies at timed transfer stations under three different levels of Intelligent Transportation Systems (ITS) technologies: the absence of ITS, the presence of Automatic Vehicle Location (AVL) and Automatic Passenger Counters (APC), and the presence of AVL only. The strategies examined were:

- Dispatching the vehicle at its scheduled departure time (also referred to as the do-nothing scenario)

- Holding a vehicle until all other coordinated vehicles arrive

- Holding a vehicle until a predefined fixed period

- Holding a vehicle until a predefined fixed period if at least one connecting vehicle is predicted to arrive during the holding time

- Holding a vehicle until a predefined fixed period if at least one connecting vehicle is predicted to arrive during the holding time with at least one transferring passenger onboard

Results showed that dispatching strategies using ITS technologies provide benefits in terms of reduction in through passenger delay as well as reduction in the number of passengers missing

their connections. Furthermore, as the vehicle delay variability decreases the ITS based strategies significantly outperform the non-ITS ones because the bus arrival time forecasts become more accurate. Similar results were obtained in a later paper [Dessouky et al., 2003] which also compared control strategies at transfer stops that depend on technologies for communication, vehicle tracking and passenger counting to those that depend solely on locally available information. An additional feature of this simulation model was that it accounted for the delay experienced by passengers waiting at downstream stops as well as that experienced by through passengers at the transfer stop where the vehicle is held. They demonstrated that technology based strategies are most advantageous when the schedule slack for the bus held at the transfer stop is zero and its line headway is large.

Hall et al. [1999] developed analytical models to determine optimal holding times for buses at transfer stations. These models minimized a total cost function which only accounted for the delay to through passengers onboard the held bus and the wait time experienced by transferring passengers if they miss their connection. For known bus arrival times and through passenger volumes, the optimal policy was shown to hold the bus on the pick-up line until the arrival time of the late bus on the delivery line. At most one local minimum for the waiting time function existed when the arrival time for the connecting buses was assumed identically normally distributed.

Chowdhury and Chien [2001] developed an algorithm that dynamically optimizes holding times at transfer stops by minimizing a time-varying total cost function. This function, however, only includes the connection delay, the missed connection costs incurred by transferring passengers and the vehicle holding cost incurred by the transit agency, with no consideration of the costs incurred by through passengers and those waiting at downstream stops who may be adversely affected by such a decision. Results showed that dynamic vehicle dispatching can significantly improve the transfer experience of connecting passengers. They also showed that as the standard deviation of the arrival time of the late vehicle increases and the transfer demand decreases, the benefits from holding a vehicle already at a transfer stop decrease.

Ting [1997] also developed algorithms to optimize holding times at transfer stops by minimizing a total cost function that considers operator cost, delay cost to passengers already onboard the held vehicle, missed connection cost to transferring passengers and delay to passengers waiting at downstream stops. He presented two approaches: a sequential approach which determines the holding times at different transfer stops sequentially and a gradient search approach which determines multiple holding times simultaneously. Ting showed that holding

times generally increase as the standard deviations of arrival times of late vehicles increase. However, when these deviations become large relative to the line headways, this dispatching control strategy is ineffective. Holding is most beneficial when the line headway for the held vehicle is large, the passenger volume onboard that vehicle is small, and the transfer passenger volume from the late incoming vehicle is relatively large.

All the previous studies presented operations control strategies as complementary actions to operations planning. Real-time dispatching measures were applied only after schedule synchronization of the connecting vehicles. However, holding strategies can also be applied independent of schedule coordination. Wong [2001], for instance, analyzed different holding strategies at the Park Street Station of the Massachusetts Bay Transportation Authority (MBTA) rail network using real-time information capabilities. A deterministic analytical model was first formulated to maximize the total expected benefits from a hold. Several assumptions, including perfect prediction capabilities and constant passenger arrival rates at stops, were later relaxed in a simulation model which addressed the same problem. Both models optimized holding times based on a total cost function which accounted for the expected impacts on all passengers, both at, and downstream of, the transfer station. Results from the analytical model indicated that holding a Green Line train produces the largest benefit when the preceding train headway is short but the following train headway is long. Sensitivity analyses on the waiting time perceptions revealed that a decrease in the ratio of the weights for out-of-vehicle time relative to in-vehicle time resulted in a significant decrease in the number of passengers adversely affected by the holding decision as well as a decrease in the total frequency of holds. The simulation model further suggested that the most advantageous time period for transfer coordination occurs in the early afternoon period between 12:00 and 4:00 pm when hourly benefits exceed 1000 passenger-minutes saved.

One noteworthy real-time transfer coordination system is used on buses of the Ann Arbor Transportation Authority (AATA) [Levine et al., 2000]. This system, referred to as the Advanced Operating System (AOS), enables digital bus-to-bus communication to improve transfer service between buses. Once a transfer is requested from vehicle x to vehicle y, a dispatch computer locates the positions of both vehicles and calculates the feasibility of holding vehicle y at the next transfer stop. However, the system does not optimize holding time based on the overall network performance effect; instead, vehicle y is held to a preset maximum time - up to 5 minutes - if a hold is accepted. Utah Transit Authority (UTA) also implemented a similar real-time transfer coordination system, known as the Connection Protection System (CP), to improve

transfer reliability for passengers connecting from the TRAX light rail trains to the lower frequency buses [Battelle Memorial Institute, 2003]. CP ensures that if a train is running late within a predetermined threshold – up to 3 minutes- its connecting buses hold at the transfer stations. The CP bases the decision to hold on TRAX real-time information and bus schedule data along with specific rules that categorize the bus routes such as bus frequency and type of service. The optimal holding time is then determined so as not to cause serious impact to the bus schedule at downstream stops.

Dispatching control decisions at transfer stops are being used nowadays by many transit agencies as one means of improving transfers by holding selected vehicles to allow transferring passengers to make their connections. Managers, operators, and field supervisors now rely on the availability of new information technologies - such as wireless communication, automatic vehicle location and automatic passenger counters - to make informed decisions with regard to these strategies by weighing a number of factors. It is not enough to deem holding appropriate if it appears to benefit only the transferring passengers. The overall system cost should be considered when making such a decision and hence the benefits and costs accrued by the different impacted parties should be accounted for. Holding might imply additional costs to the transit agency in the form of additional vehicle hours and/or additional vehicles if the half-cycle time on the held line is not maintained. It also delays passengers who are already on-board the held vehicle at the transfer stop and those waiting at downstream stops. On the other hand, vehicle holding benefits passengers who are connecting to the held vehicle. It also reduces the waiting time of those passengers arriving at the transfer stop and at downstream stops during the holding time since they are now able to board the held vehicle without waiting for the next vehicle. Consequently, holding time should be limited to a certain maximum value above which this strategy is no longer appropriate. Holding a bus indefinitely for a late connection usually causes more delay for the passengers already on the bus than the amount saved for the connecting ones.

3 TRANSFER COORDINATION MODELS

This chapter discusses the basic elements, principles and assumptions behind the development of two computer models: one for operations planning and the other for operations control. Both models aim at coordinating schedules at selected transfer stops along a transit corridor so as to improve the transfer performance. Section 3.1 summarizes the different factors that should be considered when selecting a corridor for transfer coordination analysis. The operations planning model is then developed in Section 3.2 and its structure is explained. The development and structure of the operations control model are addressed in Section 3.3.

3.1 SELECTION OF TRANSIT CORRIDOR FOR ANALYSIS

Since each transit agency has a limited budget allocated for service improvements, it is financially infeasible to apply transfer coordination to all the transit corridors in its transportation network. Prioritizing these corridors will help the agency focus its attention on the ones that represent the greatest opportunities for improvement and that can best exemplify successful applications of transfer coordination and hence justify the associated project cost.

Crockett [2002] suggested that the total number of transferring passengers to and from a corridor should be the only determining factor in the likely benefits of a transfer coordination system along that corridor. Certainly the transferring passengers will be the major beneficiaries of such a coordination scheme since they will enjoy shorter transfer waiting times. As a result, it is likely that the corridor with the highest number of transfers will benefit the most from any efforts towards improving transfers. However, there are several other factors that need to be considered that can also play a role in evaluating a transfer coordination system and hence deciding where to concentrate the coordination initiatives [Wong, 2000]. These include: the ratio of transferring passengers to through passengers at each transfer stop, the mean and standard deviation of the expected waiting time experienced by the transferring passengers, and the compatibility of headways on the connecting routes.

The ratio of transferring passengers to through passengers at each transfer stop along a corridor plays an important, yet less pronounced, role in assessing the benefits of coordination.

Although coordination benefits transferring passengers at a particular stop, it may delay or inconvenience the remaining passengers at that stop depending on the adopted strategy. The best candidate corridor for transfer coordination will have most of its transfer activity concentrated at a few transfer stops. Coordinating schedules at those stops – with high ratios of transferring passengers to through passengers – will thus benefit a high number of transferring passengers and negatively impact only a few through passengers.

The average and standard deviation of the expected waiting times experienced by transferring passengers at the different transfer stops along a corridor are also important measures in the selection process. The longer is the expected wait for a transfer, the more the potential benefits of transfer coordination. The transfer waiting time at a stop is basically the difference between the departure time of the vehicle on the destination line and the arrival time of that on the origin line. This transfer waiting time thus depends on the arrival headways on the connecting routes. The greatest potential benefits of transfer coordination occur when transferring to a low-frequency route since a long transfer waiting time will be experienced if a connection is missed.

Finally, compatibility of headways on the connecting routes should also be considered when selecting a corridor. Two headways are deemed compatible if they are equal to or are an integer multiple of each other. The higher the number of connecting routes with compatible headways, the more promising is the corridor for coordination initiatives. This is particularly true for the operations planning model which can not be applied if there are no connecting lines with compatible headways.

A transit agency should consider the above four factors when selecting the transit corridors for coordination analysis. Transfer coordination should then be exercised on each corridor for time period(s) likely to generate the greatest benefits to transferring passengers and the least inconvenience to non-transferring ones.

3.2 THE OPERATIONS PLANNING MODEL

The first model developed to assist in transit scheduling recommends a new service timetable for the vehicles operating on the selected transit corridor. This timetable is intended to allow these vehicles to meet other connecting vehicles at designated transfer stops to reduce transferring passengers' waiting time. The timetable development process involves the simultaneous application of two planning strategies: changing the terminal departure time and

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inserting slack time. The operations planning model finds optimal values for the decision variables associated with these two strategies and outputs a schedule that should minimize the transfer disutility along the corridor.

3.2.1 Basic Elements

The basic underlying principles and elements comprising the operations planning model are explored in this section. The two utilized planning strategies are first described. The restrictions behind the model application, the impacts of a new service timetable, and the evaluation measure used in the selection of this timetable are then explained.

Operations Planning Strategies

The first operations planning strategy, changing the terminal departure time, considers rescheduling the departure time from the terminal of all vehicles on the selected corridor during the period of analysis. Any change in terminal departure time would allow these vehicles to arrive at transfer locations as closely as possible to the arrival of connecting vehicles to reduce passengers' transfer waiting time. However, due to the stochastic conditions inherent in any operation, this synchronization of vehicle arrivals may not work for all trips. That is why slack time is sometimes added to the schedule of the vehicles at certain stops, referred to as timepoints, to ensure that contact occurs even if some of the trips run late. The addition of this slack time is meant to increase transfer reliability by absorbing some of the service randomness and hence increasing the probability of transfer connections. Adding slack time to the schedule at certain timepoints is thus the second operations planning strategy. The planning model does not adjust the service frequency on the analysis corridor or its connecting lines because this is seldom a favorable strategy in practice. On the contrary, these headways are assumed constant for the analysis period with their values as determined by the transit agency.

In general, the addition of slack will increase the cycle time of vehicles on the route. However, in this planning model, the addition of slack time is limited so as not to alter any of the schedule parameters of the corridor under study. The available slack time depends on the total available recovery time built into the schedule. This recovery time is often set to a certain percent, typically between 10 and 20 percent, of the scheduled trip time and is usually built in to the schedule at the route terminals. This is aimed at stabilizing the running time and headway on the route and at making sure that any variability does not propagate to the following trip.

However, often it is only mandatory that a portion of the typical recovery time is reserved at the route terminals. This time, referred to as the minimum recovery time, is sometimes part of the labor contract or simply accepted practice to allow vehicle operators a short break between trips. The remaining recovery time, referred to as slack time, is the amount that can be used by the planning model to control the vehicles' actual departure times at timepoints along the route and hence to minimize the effect of running time and headway variations en route. The scheduled departure time from each timepoint should always be respected since it is assumed that vehicles follow a schedule that is advertised to the public. To minimize the likelihood of leaving a passenger behind at a stop, vehicles are never permitted to depart before their scheduled departure time. However, if a vehicle is delayed beyond this departure time, it will depart immediately upon completion of passenger processing as shown in Figure 2-3.

Application of the Planning Model

Two restrictions have to be recognized on the transfer stops to be analyzed when applying the operations planning model to a selected transit corridor and time period. First, since the ultimate aim of the planning model is to generate a new service timetable for the vehicles operating on that corridor, only transfer stops which are also schedule timepoints are selected for analysis. Timepoints are, in fact, special stops that perform two important functions. First, they provide the vehicle operator with a way of timing or pacing his progress along the route. Second and most relevantly, they allow the transit service to be exactly specified in the form of a schedule for internal use by service planners and for external use by passengers planning their trips [Wirasinghe and Liu, 1995]. Changing the scheduled departure time from those stops, therefore, leads to a new schedule. The second restriction is to analyze only those transfer stops where at least one of the intersecting lines has a headway which is compatible with the main line on the analysis corridor. As mentioned in Section 3.1, two line headways are deemed compatible if they are identical or have an integer multiple. This headway compatibility criterion is important to ensure that a significant number of trips will benefit from the transfer coordination initiatives during the analysis period. Vehicles operating along lines – with compatible headways – will now meet at the transfer stops an integer times per hour. As a result, the possibility of making good connections greatly increases. If there are no connecting lines with headways compatible with the main route, then the operations planning model can not be applied.

A typical (simplified) transit corridor is shown in Figure 3-1. This is a route with eight stops in each direction, five of which are timepoints and five of which are transfer stops. At each transfer

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stop, four lines intersect. (As mentioned in chapter 2, the line definition in this thesis is directional; a line is a portion of the route that proceeds from one terminal to the other). This transit corridor will now be used to illustrate this selection process. The timepoint restriction limits the number of transfer stops to be analyzed to three: stops 2, 5 and 7. To finalize the selection, the headways of the connecting lines at these stops are now considered. Assume that line A (and B) of the corridor under analysis has a headway of 6 minutes, line C (and D) has a headway of 12 minutes, line G (and H) has a headway of 10 minutes and line K (and L) has a headway of 6 minutes. Since the headways of lines C and D are double those of lines A and B, these lines are compatible and stop 2 will be included in the analysis. Similarly at stop 7, both lines K and L have 6 minute headways which are identical to lines A and B, and thus this stop will also be included in the analysis. The incompatibility of headways on lines G and H with those on lines A and B disqualifies stop 5 from being included. The final output from the selection process is shown in Figure 3-2.

Figure 3-1. Corridor Representation
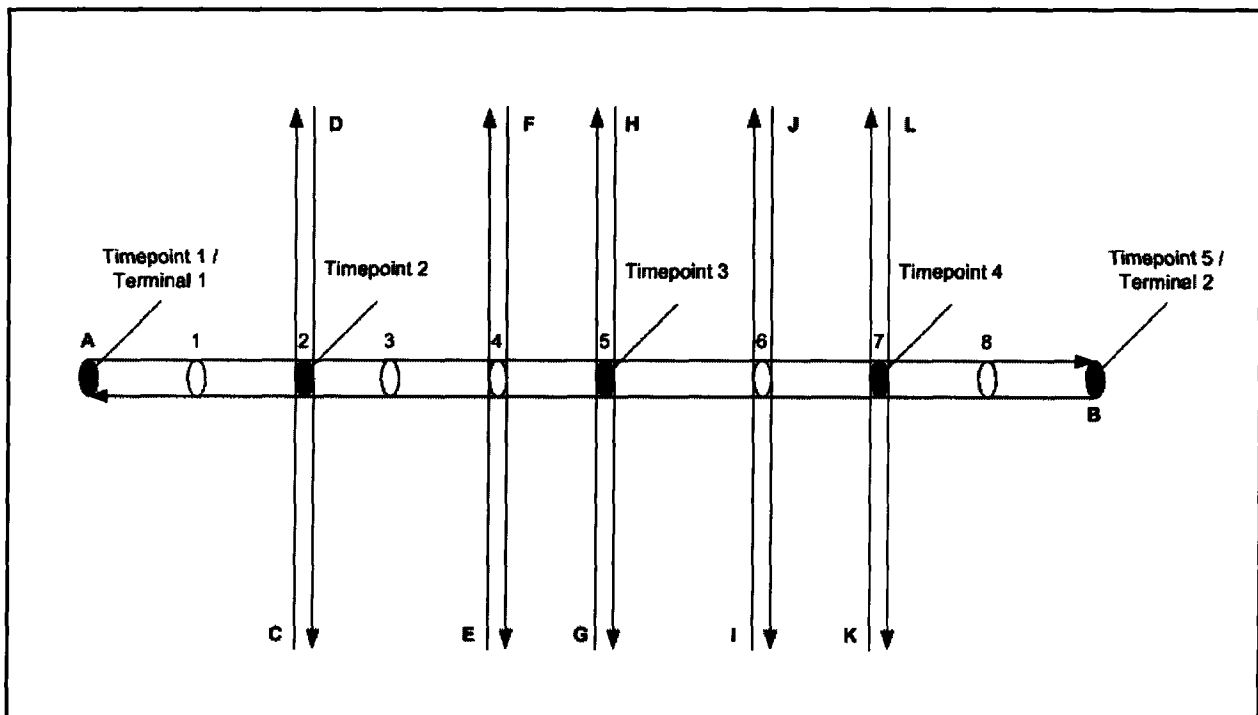
Figure 3-2. Output from Selection Process
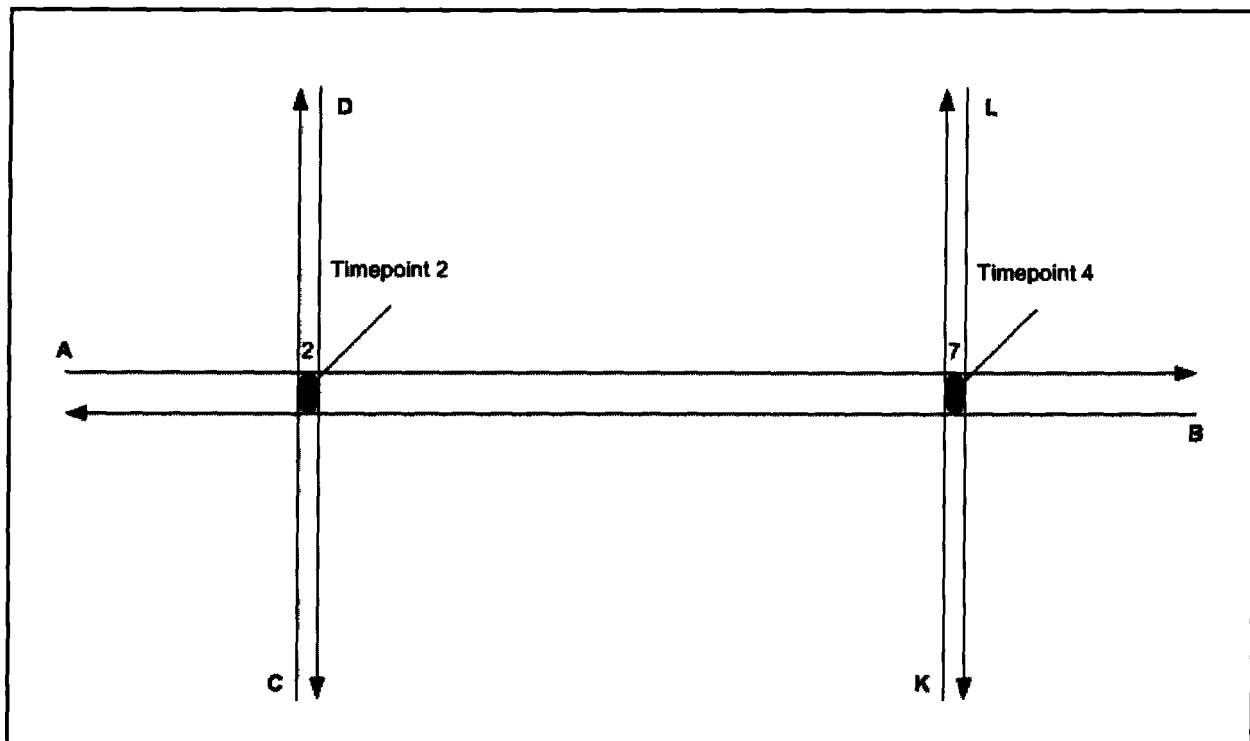
Once the transfer stops have been selected, the operations planning model can then be applied to develop a new service timetable for the chosen corridor comprising lines A and B in this example. The process of timetable development will be discussed later in the chapter. While generating a new timetable for these lines, it is assumed that the service schedules of all the routes connecting with the corridor at the selected transfer stops remain the same. The schedules of lines C, D, K and L are thus kept unchanged in the process of setting a new timetable for lines A and B.

Impacts of a New Service Timetable

Applying the operations planning model to a particular corridor is primarily meant to improve transfer coordination at selected transfer stops along that corridor by minimizing the inconvenience associated with the transfers. However, the new service timetable generated by this application should not only consider the savings in waiting times experienced by transferring passengers. The impacts of this timetable on non-transferring passengers should also be considered. Since the developed model involves the simultaneous application of two planning strategies, it is difficult to accurately predict the benefits or delays experienced by the different passenger types at each selected transfer stop.

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The separate impacts of each strategy on the potentially affected passengers were addressed in Chapter 2. Influenced passengers can actually be grouped into three categories at each transfer stop. These categories are illustrated below with reference to stop 7 in Figure 3-2.

■ P1 Passengers

These are the passengers transferring between the vehicles on lines A and K. These transferring passengers are expected to benefit the most from coordination initiatives since they should experience zero, or at least shorter, expected transfer waiting times. The passengers transferring from line K to line A are at a greater advantage, however since slack time can be added to the schedule of the vehicle on line A at stop 7 if that will minimize the number of missed connections. This strategy is not an option for line K since its schedule is assumed unchanged in the planning model.

■ P2 Passengers

These passengers arrive at the transfer stop onboard the vehicle on line A and proceed past that stop to alight at downstream destinations. If slack time is introduced in the schedule at that stop, these passengers are adversely affected since they are now delayed onboard for the duration of the slack.

■ P3 Passengers

These are the passengers who board the vehicle on line A at stop 7. These boarding passengers are assumed to know the schedule of their vehicle beforehand. Their arrival patterns at Stop 7 are assumed to remain the same with or without coordination, and hence their waiting time is assumed unchanged.

As discussed earlier, changing the vehicle departure time from the starting terminal and/or inserting slack time in its schedule at intermediate timepoints is not allowed to increase the cycle-time. Therefore, the operating cost to the transit agency does not change as a result of this model's application since the number of vehicles and the number of vehicle-hours remain the same.

Objective Function

A number of the planning models developed in the literature determine the optimal schedule based on the benefits accruing to transferring passengers only with the sole measure being the

reduction of transfer waiting time [Rapp and Gehner, 1976; Andréasson, 1977; Hall, 1985; Knoppers and Muller, 1995]. Changing the service timetable, however, can impact not only transferring passengers but also non-transferring ones if slack is introduced en route. Thus transfer waiting time should not be the sole objective in timetable selection. A timetable that minimizes the waiting time of transferring passengers while causing significant delays to non-transferring ones is not optimal. Such a timetable may degrade the overall performance of the route and worsen the overall service quality offered to passengers. Therefore, the selection of a new service timetable must be based on both the benefits and delays to all potentially affected passengers.

The measure that will be used as the basis for selecting an optimal timetable will be the total expected waiting time which is defined to include both in-vehicle delay and out-of-vehicle wait. In-vehicle delay is suffered by passengers onboard a vehicle which is waiting at a stop while out-of-vehicle wait is experienced by passengers transferring between connecting vehicles. Since waiting time is the major source of variability in any trip, it makes sense to base any schedule recommendation on the net change in the passengers' waiting time.

3.2.2   Model Assumptions

This section presents the assumptions made in the operations planning model. These assumptions allow the application of this model to transit networks with dynamic traffic conditions, multiple transfer stops and multiple routes connecting at these stops.

Minimum Connection Times

Minimum connection times are defined as the walk time needed by transferring passengers to traverse between their arriving vehicle and their destination one. Minimum connection times can vary by stop depending on its layout and physical characteristics and are included to make sure that all the transferring passengers make their connections successfully. In this model, it is assumed that the minimum connection times are deterministic.

Headways

The planning model deals with a predetermined network of transit routes with the headways on each route assumed constant for the duration of the time period being analyzed. Once the

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schedule for the first trip on a line in the transit corridor is set, this predefined sequence of headways is used to generate the schedule of all following trips on that line.

Dwell Times

The dwell time of a vehicle at a stop is the time needed by that vehicle to complete its passenger processing. This time depends on many factors including the vehicle's door characteristics, the fare payment method, and the expected number of boardings and alightings [Lin and Wilson, 1993; Aashtiani and Iravani, 2002]. The number of boardings and alightings will vary with the vehicle's preceding headway. However, since headways are assumed constant in this planning model, it is reasonable to assume that dwell times are also constant.

Half-Cycle Times

The expected travel times between any two stops are assumed constant in the model, as is the recovery time needed at each terminal. Consequently, the scheduled half-cycle times in each direction remain unchanged. This is an important assumption which implies that the offset time at terminal 2 is the same as that at terminal 1. It also implies that any addition of slack in the schedule of one direction will not affect the expected arrival/departure times at the transfer stops in the opposite direction.

Vehicle Arrival Time Distributions

Many of the planning models discussed in the literature assume deterministic vehicle arrivals [Rapp and Gehner, 1976; Andréasson, 1977; Klemt and Stemme, 1988], and those studies which use stochastic vehicle arrival time distributions are developed only for a single transfer stop [Hall, 1985; Lee and Schonfeld, 1991; Wirasinghe and Liu, 1995; Knoppers and Muller, 1995]. The planning model, developed in this research, assumes probabilistic vehicle arrival times at the selected transfer stops for both the analysis route and its connecting routes. It accommodates any arrival time distribution input by the user and estimates the total expected waiting time accordingly. For the applications presented in Chapter 5, the arrival time distribution of vehicles on each line at each stop is based on actual CTA data collected over a period of five days as will be explained further in that chapter.

Passenger Demand

Passenger demand usually varies with the level of service provided by the transit agency. As the service quality on a line improves, the demand for that line is likely to increase. However, the change in the level of service of a line should not affect passenger demand for that line if the planning horizon is relatively short [Rapp and Gehner, 1976; Andréasson, 1977]. In this model, it is assumed that both the passenger demand and transfer flows associated with any line are fixed and are not affected by any change in that line's service timetable. The through and transferring passenger volumes – input to the model – are average values taken over all the trips in the analysis period.

Passenger Time Values

Research has shown that passengers perceive in-vehicle delay differently from out-of-vehicle time, with the latter generally being more onerous. As explained earlier, in-vehicle delay is experienced by passengers onboard a vehicle that is waiting at a stop, while out-of-vehicle time is experienced by passengers transferring between their connecting routes. The operations planning model differentiates between these time perceptions. The starting assumption is that the ratio of out-of-vehicle time to in-vehicle delay is 1.5. Thus 15 minutes of in-vehicle time is valued the same as 10 minutes of time spent waiting for vehicle arrival at a stop. Incorporating distinct values of out-of-vehicle time and in-vehicle delay leads to more realistic evaluations of the costs and benefits of any planning action. These specific values, however, are not intended as a standard to use in all situations. They should be altered to reflect passenger perceptions in any application.

3.2.3   Waiting Time Calculation

As mentioned in Section 3.2.1, the measure that is used for selecting a new schedule for the corridor under study is the total expected waiting time along that corridor, TWT. This total expected waiting time changes with the service timetable on the corridor. For a particular schedule, TWT is calculated as the summation of the expected waiting times at the selected transfer stops on both lines of the analysis route (see Equation 3-1). Table 3-1 summarizes the notation used for the waiting time calculation.

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$$TWT = \sum_{i=1}^{2} \sum_{x=1}^{max\_n} WT_{x,i} \quad \textbf{\textit{Equation 3-1}}$$

The expected waiting time at any transfer stop in the direction of i, $WT_{x,i}$, is calculated as the summation of the waiting times experienced by the different impacted passengers at that stop (see Equation 3-2 where c1 and c2 represent the lines connecting with the main corridor at the transfer stop). As mentioned earlier, a new schedule affects the passengers transferring between the connecting routes and the analysis corridor as well as the through passengers along the corridor. Due to the probabilistic nature of vehicle arrivals at any transfer stop, the calculation of WT is determined from the joint probability distributions of these arrivals. However, since vehicle arrivals are assumed to vary independently on each route, the joint probabilities of arrivals may be obtained by simply multiplying the probabilities obtained separately from each vehicle arrival time distribution.

$$WT_{x,i} = \sum_{min\_a_x(i)}^{max\_a_x(i)} \left\{ \sum_{min\_a_x(c1)}^{max\_a_x(c1)} [wt_x(i,c1)+wt_x(c1,i)]*P_{a(c1)} + \sum_{min\_a_x(c2)}^{max\_a_x(c2)} [wt_x(i,c2)+wt_x(c2,i)]*P_{a(c2)} + wt_x(thr,i) \right\} *P_{a(i)}$$

Equation 3-2

The waiting time experienced by passengers transferring from line i to line j at stop x, $wt_x(i,j)$, depends on the arrival time of the vehicle on line i and the departure time of the vehicle on line j from stop x. Two cases are considered. First, the vehicle on line j departs before the passengers transferring from line i complete their connection. These transferring passengers now have to wait for the next arriving vehicle on line j (see Equation 3-3). Second, transferring passengers from line i are able to connect with the current vehicle on line j. This can occur when the transferring passengers from line i arrive either before (see Equation 3-4) or after (see Equation 3-5) the arrival time of the vehicle on line j but before its departure time from stop x.

$$wt_x(i,j) = p_x(i,j)*\{\alpha*[a_x(j+1)-a_x(i)-tt_x(i,j)]+[d_x(j+1)-a_x(j+1)]\} \quad \textbf{\textit{Equation 3-3}}$$

$$wt_x(i,j) = p_x(i,j)*\{\alpha*[a_x(j)-a_x(i)-tt_x(i,j)]+[d_x(j)-a_x(j)]\} \quad \textbf{\textit{Equation 3-4}}$$

$$wt_x(i,j) = p_x(i,j)*\{d_x(j)-a_x(i)-tt_x(i,j)\} \quad \textbf{\textit{Equation 3-5}}$$

Table 3-1. Notation for Waiting Time Calculation

$a_x(i)$	=	arrival time of the current vehicle on line i at stop x
$a_x(i+1)$	=	arrival time of the following vehicle on line i at stop x
$d_x(i)$	=	departure time of the current vehicle on line i at stop x
$d_x(i+1)$	=	departure time of the following vehicle on line i at stop x
i	=	line on the analysis corridor
$\min\_a_x(i), \max\_a_x(i)$	=	earliest/latest arrival times of current vehicle on line i at stop x
max_n	=	number of transfer stops selected for analysis
$P_{a(i)}$	=	probability of a vehicle arriving at time "a" on line I at stop x
$p_x(i,j)$	=	expected number of passengers transferring per arriving vehicle from line i to line j at stop x (pax)
$p_x(thr,i)$	=	expected number of through passengers per vehicle on line i at stop x (pax)
$slack_{x,i}$	=	amount of slack added at transfer stop x on line i (min)
$tt_x(i,j)$	=	minimum connection time from line i to line j at stop x (min)
$TN_{x,i}$	=	transfer stop x on line i
TWT	=	total expected waiting time along the corridor (min)
$WT_{x,i}$	=	expected waiting time at transfer stop x on line i (min)
$wt_x(i,j)$	=	waiting time of passengers transferring from line i to line j at stop x (min)
$wt_x(thr,i)$	=	waiting time of through passengers on line i at stop x (min)
α	=	ratio of out-of-vehicle wait to in-vehicle delay

Finally, the waiting time experienced by through passengers on line i at stop x, $wt_x(thr,i)$, depends on the arrival and departure times of the vehicle on line i at the transfer stop (see

Equation 3-6). Recall that vehicles are never permitted to depart before their scheduled departure time. However, if a vehicle is delayed beyond this scheduled departure time, it will depart immediately upon completion of passenger processing.

$$wt_x(thr,i) = p_x(thr,i)*\{d_x(i) - a_x(i)\} \quad \textbf{\textit{Equation 3-6}}$$

3.2.4   Model Structure

The main aim of the operations planning model is to identify a new service timetable for a particular corridor which improves the transfer performance at selected transfer stops. Figure 3-3 shows the general structure of this model, which involves the simultaneous application of two planning strategies: changing the terminal departure time and inserting slack time. In summary, the model first calculates the total expected waiting time associated with every feasible offset/slack time combination, selects the combination that minimizes the TWT along the corridor and recommends a new schedule based on this combination.

The model first initializes offset time to the minimum allowed value from the offset range input by the user. It also initializes slack times at the selected transfer stops in direction 1 along the analysis corridor to zero. Using this offset/slack time combination, the expected arrival and departure times at each selected transfer stop in direction 1 are determined based on the expected link travel times which are assumed constant in the model. The expected waiting times at each of these stops are then calculated based on Equation 3-2, which as previously discussed accounts for the probabilistic nature of vehicle arrivals.

The slack times at the selected transfer stops in direction 2 along the analysis corridor are now initialized to zero. Using these slack time values and the offset at terminal 2 (which is equal to that at terminal 1), the expected arrival and departure times at the selected transfer stops in direction 2 are determined. The expected waiting times at each of these stops are then calculated based on Equation 3-2. The total expected waiting time along the corridor is finally calculated according to Equation 3-1 for the given offset/slack time combination.

Since changing the schedule at the transfer stops in one direction (in terms of adding slack time) does not affect the operations plan in the opposite direction, the slack times at the transfer stops in direction 2 are now altered such that their sum does not exceed the maximum amount of slack available for that direction. The expected waiting times at the transfer stops in direction 2 as well as the total expected waiting time along the corridor are evaluated again for that offset/slack time combination. This process is repeated until all the slack time combinations in direction 2 have been analyzed for the same offset and the same slack time combinations in direction 1. The model then chooses another combination of slack times at the transfer stops in direction 1 such that the sum of these slack values does not exceed the maximum amount of slack available for that direction. The whole process of evaluating the different slack time combinations in direction 2 is then repeated with the TWT calculated and stored in each case.

This is carried out for each allowable offset value so that, at the end, the total expected waiting times of all the feasible offset/slack time combinations have been evaluated. The minimum total expected waiting time along the analysis corridor is then selected along with its offset/slack time combination. Knowing the starting time from the terminal, the link travel times, the slack times at the transfer stops in each direction and the recovery times at the two terminals, the new schedule for the first trip on that route is fully determined. The schedule for subsequent trips can then be easily obtained since headways are assumed constant for the duration of the study.

Comparing the total expected waiting time experienced by passengers in the proposed schedule with that experienced in the current schedule indicates the expected benefits of applying operations planning strategies to the transit corridor.

Figure 3-3. Operations Planning Model Structure
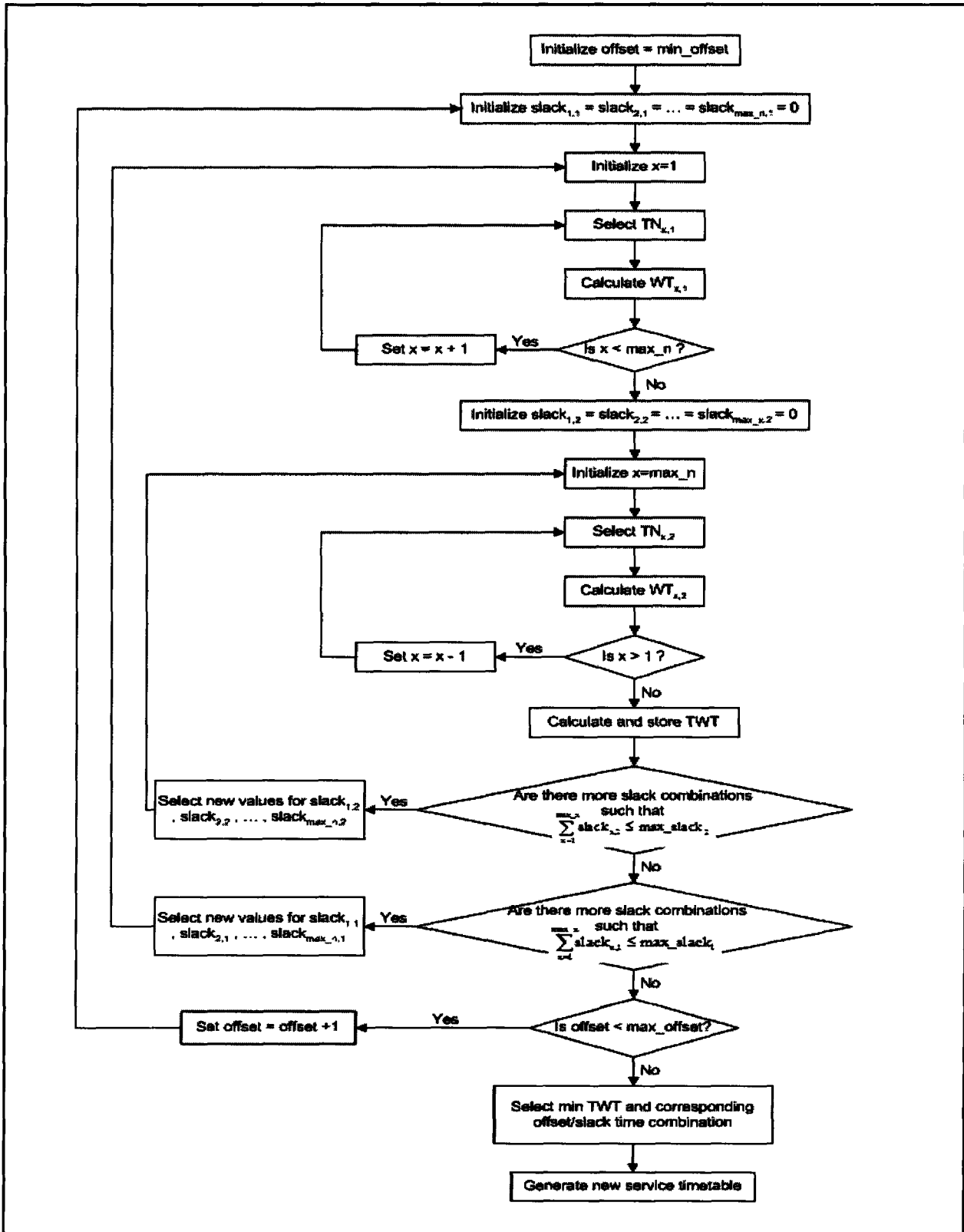
The operations planning model recommends a new service timetable that minimizes the total expected waiting time for the first trip on the analysis corridor. The choice of the offset/slack time combination is, therefore, optimal for this first trip. If the headways on all the connecting routes are equal to that on the analysis corridor, this choice of offset/slack time combination is also optimal for all the subsequent trips in the time period under study. However, if some or all of these connecting route headways are not equal to the headway on the analysis corridor, the timetable recommended by the operations planning model might not result in the minimum total expected waiting time for all the trips in the study period. This is because a schedule which produces good transfer connections between certain trips may produce poor connections between other trips if the headways on the connecting routes are not equal.

For example, suppose we have a main line A and a connecting line B with headways of ten and twenty minutes respectively. Suppose that the operations planning model recommends a new schedule on line A such that the first trip on that line (A1) arrives at the transfer stop at time t and completes its connection with the first trip on line B (B1), assuming a minimum connection time of zero minutes between the lines. Let A2 and B2 be the next trips on lines A and B after trips A1 and B1. The arrival times of A2 and B2 at the transfer stop would then be t+10 and t+20 minutes respectively assuming deterministic conditions. Although the schedule recommended by the operations planning model results in no transfer waiting time for the connection from A1 to B1, this schedule produces a wait of 10 minutes for the connection from A2 to B2. In fact, this wait will be experienced by passengers transferring from every second trip on line A. The waiting time experienced by passengers transferring from line B to line A – under the recommended schedule – will always be zero because of the higher frequency on the latter line.

In summary, the total expected waiting time calculated by the operations planning model only accounts for those trips which are similar to the first trips on the connecting routes. If the headways on all these routes are equal, then the timetable recommended by the model would produce the greatest benefits. Otherwise, the expected waiting times experienced by passengers on the remaining trips should be calculated separately for all offset/slack time combinations and the total expected waiting times along the corridor should be adjusted. A new timetable should then be recommended based upon the adjusted total expected waiting times and not upon those obtained directly from the planning model.

Referring to the example presented earlier, the timetable recommended by the operations planning model schedules the arrival of the first trip on line A (A1) at time t so that it connects

with the first trip on line B (B1). Therefore, the proposed timetable results in a transfer waiting time of zero minutes for passengers transferring between lines A and B on these first trips, as well as on similar following trips. However, since the headways on both lines are not equal, the recommended schedule might not result in the greatest benefits for the transfer stop under study when all the trips within the analysis period are considered. Post-processing is therefore applied to adjust the total waiting times obtained from the planning model for each feasible offset/slack time combination and to recommend a new service timetable accordingly.

The adopted post-processing approach first calculates the expected waiting times of the different passengers for each trip which is different from the first trip and which occurs within a one-hour block of the analysis period. It then averages these waiting times along with those obtained from the operations planning model for each passenger category separately and finally sums up the average expected transfer waiting times of all impacted passengers to arrive at the adjusted total expected transfer waiting time per trip along the corridor.

Table 3-2 summarizes this calculation for the particular offset/slack time combination in our example. As discussed earlier, the transfer waiting times of impacted passengers for the first trips and for similar following ones are zero minutes. These values are obtained from the operations planning model results. The transfer waiting times of impacted passengers for the second trip on line A as well as for similar trips within the one-hour block are calculated through post-processing to be ten minutes. Averaging these values for each passenger category and summing the averages leads to a total transfer waiting time of five minutes per trip on line A as opposed to the zero total transfer waiting time which was suggested by the operations planning model.

Table 3-2. Sample Post-Processing Calculation

Transfer Direction	Transfer Waiting Time (min)						Average Transfer Waiting Time per Trip (min)
	1st Trip	2nd Trip	3rd Trip	4th Trip	5th Trip	6th Trip	
A - B	0	10	0	10	0	10	5
B - A	0	0	0	–	–	–	0

The actual total transfer waiting times for the remaining offset/slack time combinations are calculated in a similar manner for the presented example, and a new service timetable is recommended on line A accordingly.

3.3 THE OPERATIONS CONTROL MODEL

Over the last decade, information technologies have advanced greatly so that more transit agencies are starting to make use of AVL, APC, and AFC systems to support their operations control decisions (among many other applications). One such operations control decision, which has attracted much attention in recent years, is vehicle holding at transfer stops to allow passenger transfers from connecting vehicles. For any vehicle, which is ready to be dispatched from a transfer stop, the question is whether to dispatch it immediately or to hold it for an arriving vehicle with connecting passengers. The model described in this section addresses this question. The main aim of this real-time dispatching model is to make recommendations as to whether a vehicle arriving at a transfer stop should be held for feeder vehicle arrivals. This evaluation of the holding decision is based upon the net passenger-minutes saved both for transferring and non-transferring passengers. Wong [2000] developed such a model that was applied to the transfers between the Red and Green Lines at the Park Street Station of the Massachusetts Bay Transportation Authority (MBTA). The model used in this research is an extension of Wong's since it can be applied to all connection types. As such, many of the underlying principles and assumptions comprising this model are similar to those developed by Wong.

3.3.1   Basic Elements

The basic underlying principles and elements comprising this real-time dispatching model are first explained. These include: feasibility of a hold, impacts of a hold, and basis for a hold.

Feasibility of a Hold

Not all vehicles arriving at a transfer stop are deemed eligible for holding. The feasibility of a hold is based on three factors: the schedule of the vehicle being considered for a hold, the estimated arrival time of the following vehicle on the same line, and the estimated arrival time of the closest incoming vehicle on a connecting line.

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The first factor considers the schedule of a vehicle y as it arrives at the transfer stop x. The maximum allowed holding time for this vehicle is calculated as the time remaining in the schedule of that vehicle at that point on the route excluding the minimum recovery time that is reserved at the terminal. The second factor ensures that the held vehicle y will depart the transfer stop x before the expected arrival of the following vehicle on the same line. In other words, a vehicle will never be held so long that it delays the arrival of the following vehicle. The maximum holding time is again calculated basing it, this time, on the following headway. The last factor is used to determine the holding time that is required by the transferring passengers to make their connection. This includes the estimated time needed for the incoming vehicle to arrive at the transfer stop and the minimum connection time needed for the passengers to transfer.

Holding is considered a feasible option only if the required holding time needed by the transferring passengers to complete their connection is less than or equal to the available maximum holding time based on both the schedule and following headway. Equation 3-7 depicts this feasibility requirement where H_z refers to the holding time calculated based on factor z.

$$H_3 \leq \min(H_1, H_2) \quad \textit{Equation 3-7}$$

Impacts of a Hold

Holding a vehicle at a transfer stop is primarily intended to reduce transfer waiting time at that stop. Specifically passengers transferring to the held vehicle will benefit by experiencing no waiting time for the transfer. However, transferring passengers are not the only ones affected by this decision. The impacts of holding on other passenger types at the transfer stop and at downstream stops should also be considered. There are generally six different types of passengers affected:

- P1 Passengers

These are the passengers connecting to the held vehicle from an incoming feeder vehicle. P1 passengers benefit the most from holding since they can now complete their connection to the destination line. Instead of waiting for the next incoming vehicle on the destination line, these passengers experience no wait time if a hold is implemented.

- P2 Passengers

These through passengers originate at stops upstream of the transfer stop and alight at downstream destinations. P2 passengers are adversely affected by a hold since they are delayed in-vehicle for the duration of the hold.

- P3 Passengers

These are the passengers accumulating at the transfer stop and at downstream stops over the preceding headway on the destination line. P3 passengers board the vehicle during the dwell time regardless of whether or not a hold is implemented. As such, these passengers are also negatively affected by a holding decision since they are delayed onboard the vehicle for the duration of the hold.

- P4 Passengers

P4 passengers arrive at the transfer stop and at downstream stops during the holding period and are able to board the held vehicle as a result of the hold. These passengers save time amounting to the following headway on the destination line.

- P5 Passengers

P5 passengers are a fraction of the P2 passengers who are destined to transfer at downstream stops to connecting vehicles. Holding influences these passengers' transfer waiting time at these downstream stops, either positively or negatively. As a result of holding their vehicle at the current stop, P5 passengers might miss their connections at downstream stops for instance.

- P6 Passengers

These are the passengers connecting to the vehicle on the main line at downstream stops. P6 passengers are also affected, either positively or negatively, by a holding decision depending on whether they make or miss their connections.

The additional cost to the transit agency as a result of a holding decision is assumed zero since a hold is not permitted to extend the half-cycle time of a vehicle. As discussed in the previous section, holding a vehicle at a particular transfer stop is considered a viable option only if there is enough time remaining in the schedule of that vehicle excluding the minimum recovery time at the terminal.

Basis for a Hold

Real-time transfer coordination can improve the overall performance of a transit network by improving service reliability and reducing the disutility associated with transfers. Some of the benefits of holding include the minimization of missed connections and the shortening of transfer waiting time. However, these measures can not be used as the sole criteria for holding a vehicle since they reflect the effect of such a decision on transferring passengers only. When making such control decisions, the transit agency should consider the overall network effects and should ensure that the level-of-service experienced by non-transferring passengers is not so drastically reduced.

The measure that will be used as the basis behind any holding decision will be the net passenger-minutes saved from a hold. This total net benefit measures the difference in waiting times for passengers benefiting from the hold and those being delayed by it. Since waiting time is the major source of variability in any trip, it makes sense to base any holding recommendation on the net change in the passengers' waiting time and to use such a measure for evaluating the effectiveness of a hold.

Some transit agencies, however, might not feel comfortable basing their dispatching decision on just a positive total net benefit measure. If the net passenger-minutes saved is negligible, holding a vehicle is a plausible but not necessarily a wise option since it will not result in significant benefits. That is why a minimum holding criterion is utilized as the basis for holding decisions. Real-time holding is implemented at a transfer stop only when the net passenger-minutes saved exceeds this minimum holding threshold.

3.3.2   Model Assumptions

Some of the principles and assumptions behind the operations planning model also hold true for the operations control model. This section discusses new issues that are introduced to this real-time dispatching model as well as areas that are treated differently than in the operations planning model. Any issues, not discussed in this section, are treated in the same manner as in the operations planning model.

Holding Characteristics

Holding time is defined as the time vehicle x is waiting at a transfer stop for an incoming feeder vehicle y. The start of this holding time depends on the estimated arrival time of vehicle x and the nature of the transfer stop. If vehicle x arrives at a transfer stop, which is a timepoint, and completes its passenger processing before its scheduled departure time from that timepoint, then holding begins at the scheduled departure time. Otherwise, holding begins after the conclusion of the initial dwell time of vehicle x. The duration of the hold depends on the arrival time of vehicle y. It is assumed that if vehicle x is held, it will not leave the transfer stop until all the passengers from the feeding vehicle y have transferred. It is also assumed that all these transferring passengers are able to board the current held vehicle x without any capacity concerns.

Vehicle Characteristics

A real-time information system is capable of predicting the arrival times of vehicles at the stops based on AVL data. In the absence of AVL data, the agency can only resort to communication between its field supervisors, vehicle operators and control center to get approximate locations of its vehicles and estimate their arrival times at stops. In most cases it will not be practical to employ holding in the absence of an AVL system. Referring to Figure 3-1 and assuming that the vehicle arriving at stop 2 on line A is being considered for a hold, the real-time information system will be used to predict the arrival times of the closest connecting vehicles at that stop arriving on lines C and D as well as the arrival time of the following vehicle on line A. As explained earlier, the expected arrival times of the connecting vehicles on lines C and D are needed to estimate the required holding time that will guarantee a connection. The expected arrival time of the following vehicle on line A limits the time the current vehicle may be held for. Closely following vehicles make holding less attractive due to the possibility of bunching and the reduction in benefits. The prediction of arrival times of the arriving and following vehicles at the transfer stop and at downstream stops is important for the calculation of the waiting times experienced by the different passenger categories, both with and without holding.

The preceding headways on the connecting lines at the different stops are based upon the detection times of the information system for the current and preceding vehicles on each of these lines respectively. Preceding headways are used to estimate the potential passenger loads at each stop as well as the potential number of boarders and the potential number of

passengers transferring between connecting lines at those stops. Long headways result in greater than normal loads, allow more passengers to accumulate at these stops, and leads to a higher transfer demand at transfer stops.

Passenger Characteristics

Real-time information systems can also generate estimates of the number of passengers onboard a vehicle approaching a transfer stop based on historical manual or APC system data and headways from an AVL system. Historical rates can be used to estimate the number of passengers transferring from that vehicle at that stop as well as the number of non-transferring passengers who will proceed to alight at downstream destinations.

Passenger through, arrival, and transfer rates at all stops on all lines are assumed to be deterministic in the operations control model. These rates – calculated in passengers/minute - are average values taken over the period of analysis. Consequently, they reveal nothing about the minimum and maximum through, arrival, and transfer rates witnessed throughout the period. The implication of this assumption can be reduced by shortening the analysis periods to minimize the variability of passenger rates within each.

3.3.3   Waiting Time Calculation

As mentioned in Section 3.3.1, the measure that is used for evaluating any holding decision is the total net benefits resulting from such a decision. To arrive at this measure, the waiting time of all impacted passengers at, and downstream of, the transfer stop must be calculated for both the no-holding and holding scenarios. Before the waiting time calculation though, the number of impacted passengers in each category must be estimated. Table 3-3 summarizes the notation used for estimating the number of impacted passengers and their waiting time.

The number of through passengers onboard the vehicle on the main line at the transfer stop is estimated as shown in Equation 3-8 by multiplying the through passenger rate and the preceding headway of that vehicle at that stop.

Table 3-3. Notation for Waiting Time Calculation

- -

$a_x(i)$	=	arrival time of current vehicle on line i at stop x
$a_x(i+1)$	=	arrival time of following vehicle on line i at stop x
$d_x(i)$	=	departure time of current vehicle on line i at stop x
$d_x(i+1)$	=	departure time of following vehicle on line i at stop x
$holding$	=	required holding time (min)
max_n	=	number of stops analyzed including the current transfer stop
p_{thr}	=	number of through passengers onboard the vehicle on the main line at the transfer stop (pax)
$p_x(i)$	=	number of passengers waiting to board a vehicle on line i at stop x (pax)
$p_x(i/hold)$	=	number of passengers who board a vehicle on line i at stop x during the holding time (pax)
$p_x(i,j)$	=	number of passengers transferring from line i to line j at stop x (pax)
$pr\_h_x(i)$	=	preceding headway of the vehicle on line i at stop x (min)
$s_x(i/hold)$	=	time savings of passengers who board a vehicle on line i at stop x during the holding time (min/pax)
$tt_x(i,j)$	=	minimum connection time from line i to line j at stop x (min)
TWT	=	total waiting time in the system
wt_{thr}	=	waiting time of through passengers onboard the vehicle on the main line at the transfer stop (min/pax)
$wt_x(i)$	=	waiting time of passengers boarding a vehicle on line i at stop x (min/pax)
$wt_x(i,j)$	=	waiting time of passengers transferring from line i to line j at stop x (min/pax)
α	=	ratio of out-of-vehicle wait to in-vehicle delay
$\lambda_x(i,j)$	=	passenger transfer rate from line i to line j at stop x (pax/min)
λ_{thr}	=	passenger through rate at the transfer stop (pax/min)
$\lambda_x(i)$	=	passenger arrival rate to board a vehicle on line i at stop x (pax/min)

- -

$$p_{thr} = \lambda_{thr} * pr\_h_x(i) \quad \textbf{\textit{Equation 3-8}}$$

The number of passengers waiting to board a vehicle on the main line at or downstream of the transfer stop is calculated in a similar fashion according to Equation 3-9.

$$p_x(i) = \lambda_x(i) * pr\_h_x(i) \quad \textbf{\textit{Equation 3-9}}$$

The waiting time experienced by each of these two passenger types is estimated as in Equation 3-10 by subtracting the departure time of the vehicle on the main line from its arrival time at a particular stop.

$$wt_{thr} = wt_x(i) = d_x(i) - a_x(i) \quad \textbf{\textit{Equation 3-10}}$$

The number of passengers transferring from line i to line j at a particular stop is estimated as in Equation 3-11 by multiplying the passenger transfer rate from line i to line j and the preceding headway on line i at the stop.

$$p_x(i,j) = \lambda_x(i,j) * pr\_h_x(i) \quad \textbf{\textit{Equation 3-11}}$$

Similarly to the operations planning model, the waiting time experienced by each of these transferring passengers is a function of the arrival time of the vehicle on line i and the departure time of the vehicle on line j at stop x. Equation 3-12 shows the waiting time calculation if the transferring passengers miss their connection. The waiting time experienced by passengers who are ready to transfer before the arrival of their destination vehicle is shown in Equation 3-13. Finally, Equation 3-14 shows the waiting time calculation when passengers transferring from line i arrive after the arrival of their destination vehicle but before its departure from stop x.

$$wt_x(i,j) = \alpha * [a_x(j+1) - a_x(i) - tt_x(i,j)] + [d_x(j+1) - a_x(j+1)] \quad \textbf{\textit{Equation 3-12}}$$

$$wt_x(i,j) = \alpha * [a_x(j) - a_x(i) - tt_x(i,j)] + [d_x(j) - a_x(j)] \quad \textbf{\textit{Equation 3-13}}$$

$$wt_x(i,j) = d_x(j) - a_x(i) - tt_x(i,j) \quad \textbf{\textit{Equation 3-14}}$$

If the vehicle on the main line is held at the transfer stop for an incoming connecting vehicle, then there is one other passenger category affected by such a decision. These passengers arrive during the hold and save time since they can now board the current vehicle on the main

line without waiting for the following one. The number of these passengers and their waiting time savings are estimated as in Equations 3-15 and 3-16 respectively.

$$p_x(i/hold) = \lambda_x(i) * holding \qquad \textbf{Equation 3-15}$$

$$s_x(i/hold) = \alpha * [a_x(i+1) - d_x(i)] + [d_x(i+1) - a_x(i+1)] \qquad \textbf{Equation 3-16}$$

The total waiting time of all impacted passengers is calculated by summing the different waiting times at, and downstream of, the transfer stop where a hold is considered as shown in Equation 3-17, where c1 and c2 correspond to the lines connecting with the main line at the different transfer stops.

$$TWT = wt_{thr} * p_{thr} + \sum_{x=1}^{max\_n} [wt_x(i) * p_x(i) + wt_x(i,c1) * p_x(i,c1)$$
$$+ wt_x(i,c2) * p_x(i,c2) + wt_x(c1,i) * p_x(c1,i) + wt_x(c2,i) * p_x(c2,i)] \qquad \textbf{Equation 3-17}$$

This is carried out for both the no-holding and holding scenarios. (If a "ready" vehicle is held at a transfer stop, its departure time is shifted forward by the required holding time). Total net benefits or the net passenger-minutes saved are then calculated by subtracting the total waiting time for the no-holding scenario from the total waiting time for the holding scenario (which also includes the time savings of passengers now able to board the current vehicle). If this difference exceeds the minimum holding threshold set by the transit agency, the "ready" vehicle is held at the transfer stop for the arrival of the incoming connecting vehicle.

3.3.4   Model Structure

This section describes the process adopted for evaluating whether a vehicle, which is ready to be dispatched from a transfer stop, should be held for an incoming feeder vehicle arrival. To calculate the change in waiting times of the different passenger types, vehicle location data is needed to predict vehicle arrival times and passenger demand throughout the transit system. It is thus important that this holding or dispatching decision be updated whenever the control system has new vehicle location data.

Figure 3-4 will be used to illustrate the general model. Assume that a vehicle x arriving at stop 2 on line A is ready to depart at its scheduled departure time. However, the next arriving vehicle y on connecting line C is expected to arrive in one minute and the next arriving vehicle z on

connecting line D in three minutes. Vehicle x can either be dispatched immediately, held one minute for vehicle y, or held three minutes for both vehicles y and z, assuming a minimum connection time of zero minutes. The decision to hold vehicle x for vehicle y is evaluated first since the arrival time of that vehicle is the closest. If vehicle x is held for the arrival of vehicle y, then the control model is applied again at the end of the holding period to decide whether vehicle x should then be dispatched immediately or held further for the arrival of vehicle z. This dispatching decision is based on an evaluation of the change in waiting times to impacted passengers both at transfer stop 2 and at the downstream stops 3 through 8.

Figure 3-4. Control Model Application
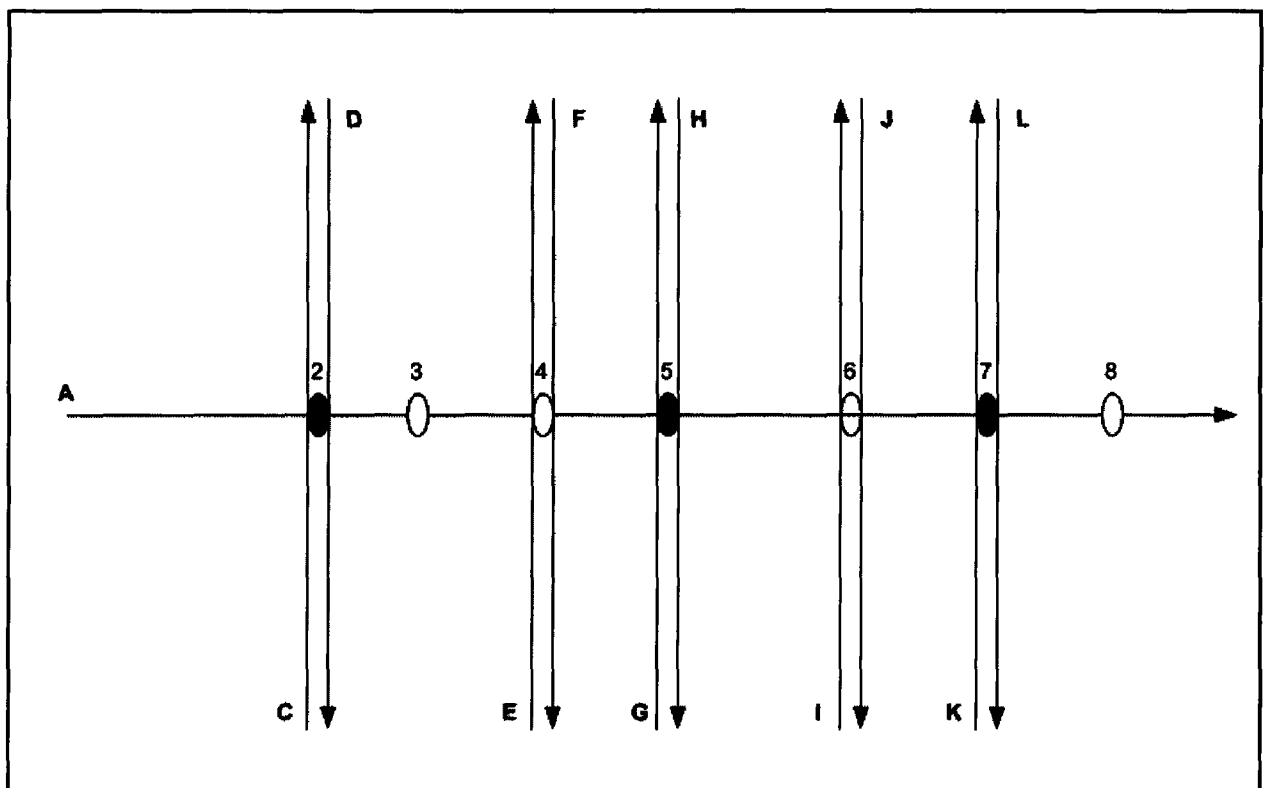
Figure 3-5 shows the general structure of the operations control model, which is split into two distinct phases. Phase I evaluates the feasibility of a holding action and calculates the holding time needed to allow transferring passengers to complete their connection. Phase II estimates the number of impacted passengers and their respective waiting time savings/delay leading to a recommended course of action based on maximizing the net passenger benefits.

Figure 3-5. Operations Control Model Structure

```
                    ┌─────────────────────────────────────┐
                    │  1. Transit vehicle arrives at a     │
                    │     transfer stop                    │
                    └─────────────────────────────────────┘
                         │        │         │
     ┌───────────────────┘        │         └──────────────────┐
     ▼                            ▼                            ▼                         ▼
┌──────────────┐  ┌──────────────┐  ┌──────────────┐  ┌──────────────┐
│ 2. Maximum   │  │ 3. Arrival   │  │ 4. Arrival   │  │ 9. Arrival   │
│ holding      │  │ time of      │  │ time of      │  │ time of      │
│ duration     │  │ following    │  │ closest      │  │ closest      │
│ based on the │  │ vehicle on   │  │ incoming     │  │ incoming     │
│ current      │  │ the same     │  │ vehicle from │  │ vehicle from │
│ schedule is  │  │ line is      │  │ an           │  │ the second   │
│ determined   │  │ estimated    │  │ intersecting │  │ intersecting │
└──────────────┘  └──────────────┘  │ line is      │  │ line is      │
                                     │ estimated    │  │ estimated    │
                                     └──────────────┘  └──────────────┘
                         ▼                  ▼
                  ┌──────────────┐  ┌──────────────┐
                  │ 3a. Maximum  │  │ 4a. Minimum  │
                  │ holding      │  │ holding      │
                  │ duration     │  │ duration for │
                  │ based on the │  │ a good       │
                  │ following    │  │ connection is│
                  │ headway is   │  │ determined   │
                  │ determined   │  │              │
                  └──────────────┘  └──────────────┘
```

Phase I

Is holding viable? ──No──▶ 5. Dispatch vehicle immediately from the transfer stop

Yes

- -

Phase II

6. Arrival times of preceding, current and following vehicles approaching the current transfer stop or downstream stops are predicted

7. Number of impacted passengers at and downstream of the transfer stop are estimated

8. Benefits and Delays of a hold are evaluated and the net passenger-minutes saved is calculated

Are minutes saved greater than minimum threshold? ──No──▶

Yes

10. Hold the vehicle for the arrival of the incoming feeder vehicle

As discussed in Section 3.3.1, holding a "ready" vehicle is feasible only if Equation 3-7 is satisfied. The maximum time, H_1, vehicle x can wait at stop 2 without increasing its half-cycle time is first determined. This time is the leeway that is remaining in the schedule of vehicle x at that point on the route excluding the minimum recovery time required at terminal 2. The estimated arrival time of the following vehicle on the same line determines the following headway of vehicle x which in turn determines H_2, the maximum holding time at stop 2 that will result in any benefits. Finally, the minimum holding time that is needed by the passengers transferring from vehicle y to vehicle x at stop 2 to complete their connection, H_3, is estimated based on the expected arrival time of vehicle y at stop 2 and the minimum connection time. If Equation 3-7 is not satisfied, vehicle x is dispatched immediately from stop 2. Otherwise, holding is deemed a feasible option, the required holding time is H_3, and the model proceeds to Phase II.

Phase II estimates the number of impacted passengers and their respective waiting time savings/delay as a result of a hold according to the equations presented in the previous section. Estimates of the arrival times of the preceding, current and following vehicles on all the lines approaching the current transfer stop and all downstream stops are first determined. These estimates are needed to determine the preceding and following headways on each line at each stop. Preceding headways are used to estimate of the number of impacted passengers in each category at each stop and the following headways are used to estimate the waiting time savings/delays for each passenger group. The overall net benefits to all impacted passengers along the transit corridor is finally calculated and compared to the minimum holding threshold set by the transit agency. If the net passenger-minutes saved equals or surpasses the minimum holding threshold, holding vehicle x for the arrival of vehicle y is appropriate. Otherwise, the decision to hold vehicle x for the arrival of vehicle z is evaluated by repeating the same procedure.

In actual operation, vehicle locations in real time can be relayed to the control center and/or field supervisors. Estimates of arrival times and the number of through, transferring and arriving passengers can then be made for each vehicle at each stop. This data can be used to make an informed decision as to whether to hold or dispatch a "ready" vehicle at a transfer stop. In this thesis – due to the absence of such prediction capabilities – a simulation approach is adopted which draws from arrival time distributions input by the user for the preceding, current, and following vehicles on each line at each stop on the analysis corridor. For the case studies, these

arrival time distributions are obtained from data collected by the AVL System and averaged over all the runs in the analysis period.

In actual operation, data on vehicle locations in the transit network is updated periodically, each time adding more certainty to the prediction of the actual vehicle arrival times. To represent this phenomenon in our research, the arrival time distributions based on the AVL System are assumed representative only for those vehicles which are expected to arrive at the stops on the analysis corridor at least fifteen minutes after the vehicle at the transfer stop under study is ready to be dispatched. The arrival time distributions of the remaining vehicles (i.e. those whose expected arrival times at the stops on the analysis corridor are within fifteen minutes from the time the vehicle at the transfer stop under study is ready to be dispatched) are modified from the original AVL-based distributions to reflect the higher level of certainty in prediction capabilities. A sample adjustment to a vehicle arrival time distribution is shown in Figure 3-6. If the vehicle is more than fifteen minutes away from its stop at the time of analysis, the arrival time distribution based on the AVL System data is used. However, if the vehicle is closer to its stop, its arrival time distribution is modified with a lower variance.

Figure 3-6. Hypothetical Arrival Time Distribution

Proximity of a vehicle arriving at a stop on the analysis line (min)   — - — · 15 — — — 10 ——— 5
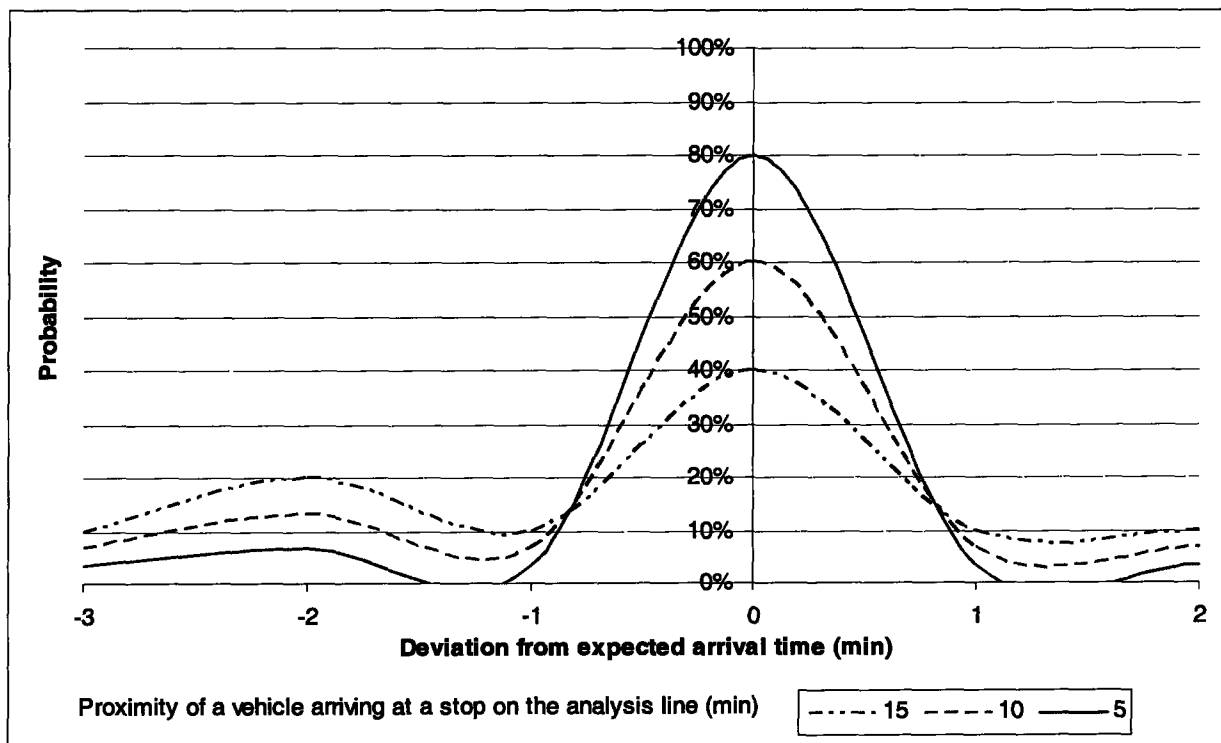
4   GENERAL APPLICATION

In this chapter, the operations planning and operations control models developed in Chapter 3 are tested to illustrate their applicability in coordinating transfers along a transit corridor. Section 4.1 describes the characteristics of the corridor used for these applications. Section 4.2 presents the results for the base scenario when the operations planning model is applied. The sensitivity of the decision variables and the model results to factors including headways, bus arrival time variance, transfer volumes and passenger time values is also explored. The results for the application of the operations control model are presented in Section 4.3. A similar set of sensitivity analyses are then presented and discussed.

4.1   CORRIDOR DESCRIPTION

The corridor used for these applications is shown in Figure 4-1. The analysis on this corridor will be restricted to one direction only to better explore the results of the transfer coordination models and to better illustrate their expected benefits. Line A runs between the two terminals, stops 1 and 7, making five intermediate stops along the way, only two of which are transfer stops. Lines B and C connect with Line A at stop 3 and Lines D and E connect with Line A at stop 5. These two stops are also timepoints for which there are scheduled departure times.

The analysis is carried out for the period 9:00 am to noon since previous studies suggest that the benefits accrued from transfer coordination initiatives are greatest during off-peak periods when headways are higher. The baseline values for the headways, passenger demands, and other related parameters are selected based on actual data from CTA routes to represent realistic operating conditions. Although actual empirical distributions based on CTA AVL data will be used for bus arrival times in Chapter 5, a symmetrical triangular distribution will be used to represent bus arrival times in this chapter. Such a distribution is representative of several CTA routes analyzed. Buses on each line are thus assumed to arrive at a stop up to three minutes earlier or three minutes later than their scheduled departure times. The baseline inputs are summarized in Table 4-1.

Figure 4-1. Corridor Representation
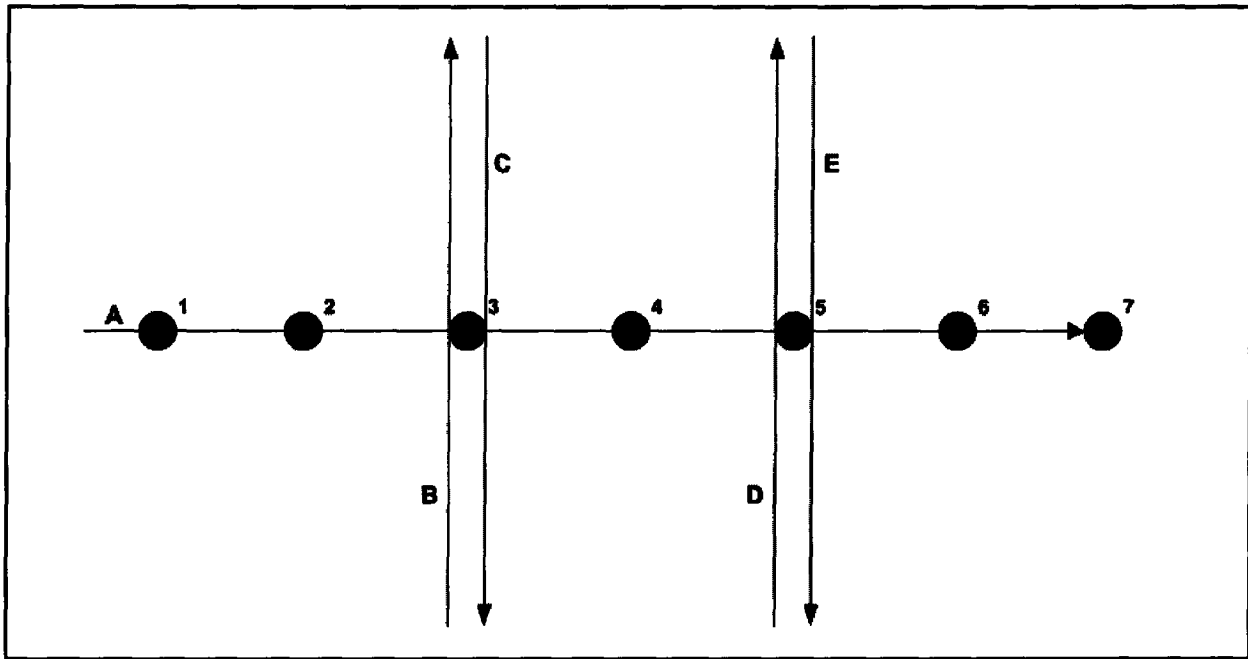
Table 4-1. Corridor Characteristics

Current Timetable of 1ˢᵗ Trip on Line A

Stop 1	Stop 3	Stop 5	Stop 7
9:00	9:10	9:25	9:45

Scheduled Departure Times of 1ˢᵗ Connecting Trips on Intersecting Lines

	Line B	Line C	Line D	Line E
Stop 3	9:07	9:11	–	–
Stop 5	–	–	9:23	9:26

Line Headways (minutes)

Line A	Line B	Line C	Line D	Line E
10	20	20	10	10

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Symmetrical Triangular Distribution

Deviation from Schedule (min)	-3	-2	-1	0	1	2	3
Probability	0.02	0.11	0.22	0.30	0.22	0.11	0.02

Passenger Transfer Volumes to Line A (pax/trip on connecting line)

Line B	Line C	Line D	Line E
1	1	1	2

Passenger Transfer Volumes from Line A (pax/trip on Line A)

Line B	Line C	Line D	Line E
1	1	2	1

Through Passenger Volumes on Line A (pax/trip on Line A)

Stop 1	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6	Stop 7
–	30	25	21	18	10	–

User-Related Parameters

Departure Offset Time	Offset time ranges from 0 to 9 minutes
Minimum Connection Time	Time to transfer between any two connecting lines at any stop is 2 minutes
Time Ratio	Ratio of out-of-vehicle wait to in-vehicle delay is 1.5
Recovery and Slack Times	Minimum recovery time at stop 7 is assumed 5 min. Slack time on Line A is also assumed 5 min.

4.2 OPERATIONS PLANNING MODEL APPLICATION

This section covers the application of the operations planning model to the selected corridor. The results of the base scenario are presented and discussed first, followed by sensitivity analyses of the decision variables to exogenous factors including headways, vehicle arrival time variance, transfer volumes and passenger time values.

4.2.1 Base Scenario

In the base scenario, both transfer stops 3 and 5 are included in the analysis. These stops are timepoints and their connecting lines have headways compatible with the headway on Line A. The recommended timetable generated by the model for the first trip between 9:00 am and noon is shown in Table 4-2 below. This timetable proposes dispatching all vehicles four minutes later from stop 1 with no slack time inserted in the schedule at any of the timepoints. Thus the half-cycle recovery time (ten minutes) is maintained at the terminal, stop 7.

Table 4-2. Recommended Service Timetable for Line A

Stop 1	Stop 3	Stop 5	Stop 7
9:04	9:14	9:29	9:49

To arrive at this schedule, the planning model analyzed all the allowed offset/slack time combinations and selected the values for these decision variables – three in this case – which minimized the total expected waiting time per trip on Line A. The optimal combination – *offset = +4, slack at stop 3 = 0, slack at stop 5 = 0* – defines a new service timetable which results in a 24% reduction in the total expected waiting time per trip. Recall that waiting time includes both in-vehicle delay experienced by through passengers and out-of-vehicle wait experienced by transferring passengers. Since no slack time is recommended in the schedule of Line A, the expected travel time of through passengers does not change (because it is not affected by a change in offset time) and hence the expected transfer waiting time of transferring passengers becomes the only element of interest.

The recommended timetable has no slack time inserted at either transfer point. This is due to a combination of the randomness of the vehicle arrival times at the transfer stops, the short headway on Line A, the low number of transferring passengers to Line A who are the main

beneficiaries from adding slack, and the high number of through passengers on Line A who are adversely impacted when slack time is inserted. Consequently, this reduction in the total expected transfer waiting time per trip can be attributed solely to the change in terminal departure time. Figure 4-2 shows the effect of changing the departure time from the terminal of Line A vehicles on the expected transfer waiting time per trip on that line for the two transferring passenger types: T1, the passengers transferring to Line A, and T2, the passengers transferring from Line A.

Figure 4-2. Expected Transfer Waiting Time per Trip on Line A vs. Offset Time
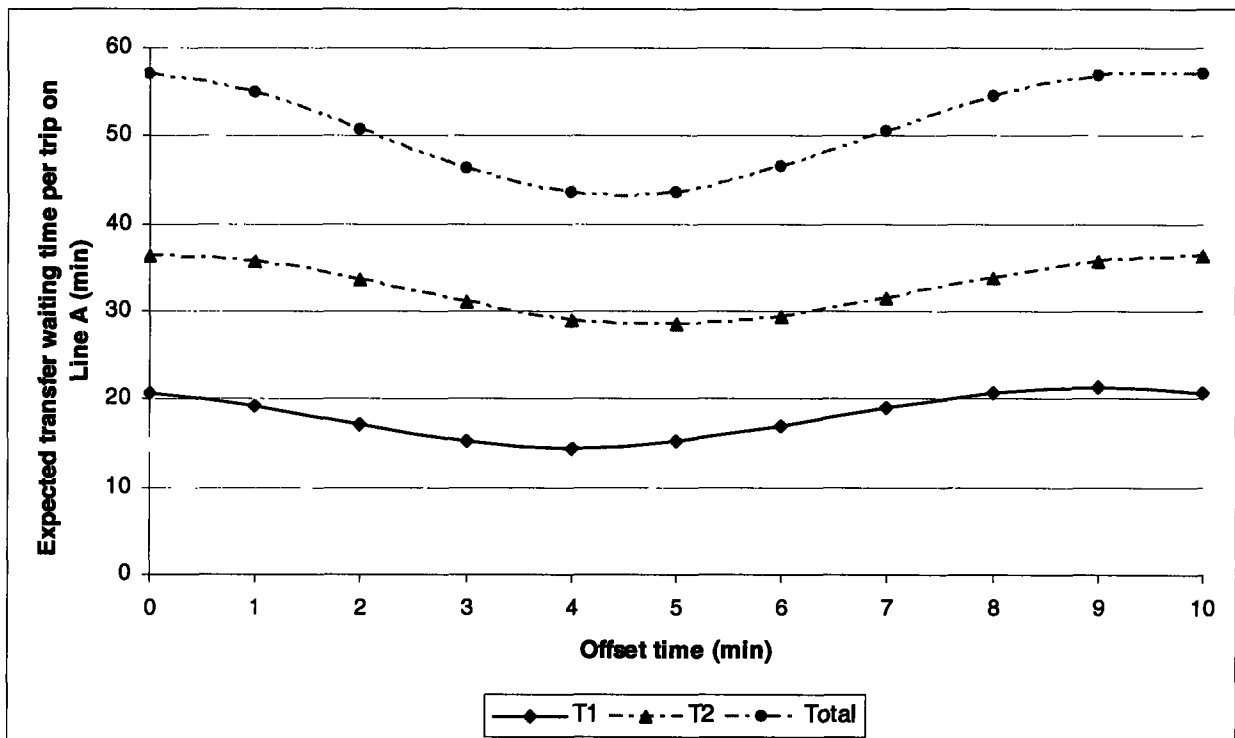
As the offset time increases from 0 to 9 minutes, the expected transfer waiting time per trip of both T1 and T2 passengers change. The minimum (maximum) expected transfer waiting time per trip of T1 passengers is approximately fourteen minutes (twenty one minutes). The minimum (maximum) expected transfer waiting time per trip of T2 passengers is approximately twenty nine minutes (thirty seven minutes). This higher expected transfer waiting time of T2 passengers is mainly due to the higher headways on Lines C and D. Since the headway on Line A is only ten minutes, vehicles arrive more frequently on this line and hence T1 passengers experience – on average – shorter expected transfer waiting times than T2 passengers. As a result of the new service timetable, the expected transfer waiting time of T1 passengers

decreases by 31% from 5.2 minutes/passenger to 3.6 minutes/passenger. That of T2 passengers decreases by a smaller magnitude of 20% from 7.3 minutes/passenger to 5.8 minutes/passenger. Overall, the expected transfer waiting time decreases from 6.3 minutes/passenger to 4.8 minutes/passenger. For this new schedule, there are 40% more passengers benefiting from the recommended timetable than are negatively affected by it (passenger-benefit ratio). On average, the expected time saved per passenger benefiting is about three minutes, whereas each negatively affected passenger is impacted by less than one and a half minutes. Transfer coordination thus proves to be a favorable option for the base scenario.

4.2.2   Further Analysis

The expected results from the application of the operations planning model are analyzed in this section when various factors are altered. The sensitivity of the decision variables to the change in these factors is also addressed. The following baseline parameters are varied: headway on Line A, vehicle arrival time variance, transfer demands to Line A, and passenger time values.

Influence of Headway on Line A

The headway on Line A is varied to investigate the effects on the optimal offset and slack times and the expected benefits of transfer coordination. All the other baseline parameters are assumed to remain the same. Table 4-3 shows the results when headways are 5 and 20 minutes. The first important observation is that optimal slack times at stops 3 and 5 remain zero across all headways. This is expected given the low ratio of the number of transferring passengers to Line A to the number of through passengers at those stops. The time savings experienced by transferring passengers if slack were added can not compensate for the additional delay incurred by the through passengers. Under all these scenarios, changing only the terminal departure time as the headway on line A changes is far preferable to adding slack time at the transfer stops along the line. The model recommends dispatching all vehicles on Line A four minutes later than their current scheduled departure time when the headway is five minutes and fifteen minutes later when the headway is twenty minutes.

It should be noted that the fifteen minute offset for the twenty-minute headway case means that buses arrive only one minute later than every second bus in the ten-minute headway timetable. This shows that the recommended timetable is quite stable even across different headways.

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Table 4-3. Sensitivity to Headway on Line A

Headway (min)	Offset Time (min)	Slack Time (min)	Expected Transfer Waiting Time per Trip on Line A (min)					
			T1 Passengers		T2 Passengers		All Passengers	
			C	R	C	R	C	R
5	4	0	4.0	3.9	32.4	32.3	36.4	36.2
10	4	0	20.8	14.4	36.4	29.0	57.1	43.5
20	15	0	63.9	53.5	42.3	22.2	106.3	76.0

C: current schedule, R: recommended schedule

Figure 4-3 shows the effect of changing the headway on Line A on the total expected transfer waiting time per trip for both current and recommended schedules. At very short headways, there are few benefits from coordinating transfers on Line A. Because vehicles run frequently on that line, the expected waiting time of T1 passengers is very short even in the current timetable. On the other hand, the expected waiting time of T2 passengers can not be reduced since many of these passengers still have to wait for the vehicles on their ten and twenty minute headway destination lines (compared to the five minute headway on their arriving line). As the Line A headway increases, the benefits from transfer coordination increase substantially. At a headway of twenty minutes, the percentage reduction in the total expected transfer waiting time per trip on Line A is about 29%. At such long headways, transfer coordination becomes an effective strategy since it can reduce the expected waiting time of both T1 and T2 passengers. Both passenger types will suffer long expected waiting times, on average, if their connecting vehicles do not arrive at times to allow good connections. The expected transfer waiting time per trip of T2 passengers, however, is smaller than that of T1 passengers – in both the current and recommended timetables – because three out of five T2 passengers transfer to Lines D and E with ten-minute headways. Table 4-3 also shows that the percentage reduction in expected transfer waiting time of T2 passengers is higher than that of T1 passengers (47.7% vs. 16.3%) as a result of coordinating transfers. This is because many of the T1 passengers (60%) transfer from Lines D and E and, even with coordination, they still have to wait for the vehicles on their twenty-minute destination line, Line A (compared to the ten-minute headway on their arriving line).

Figure 4-3. Expected Benefits vs. Headway on Line A

Figure 4-3. Expected Benefits vs. Headway on Line A
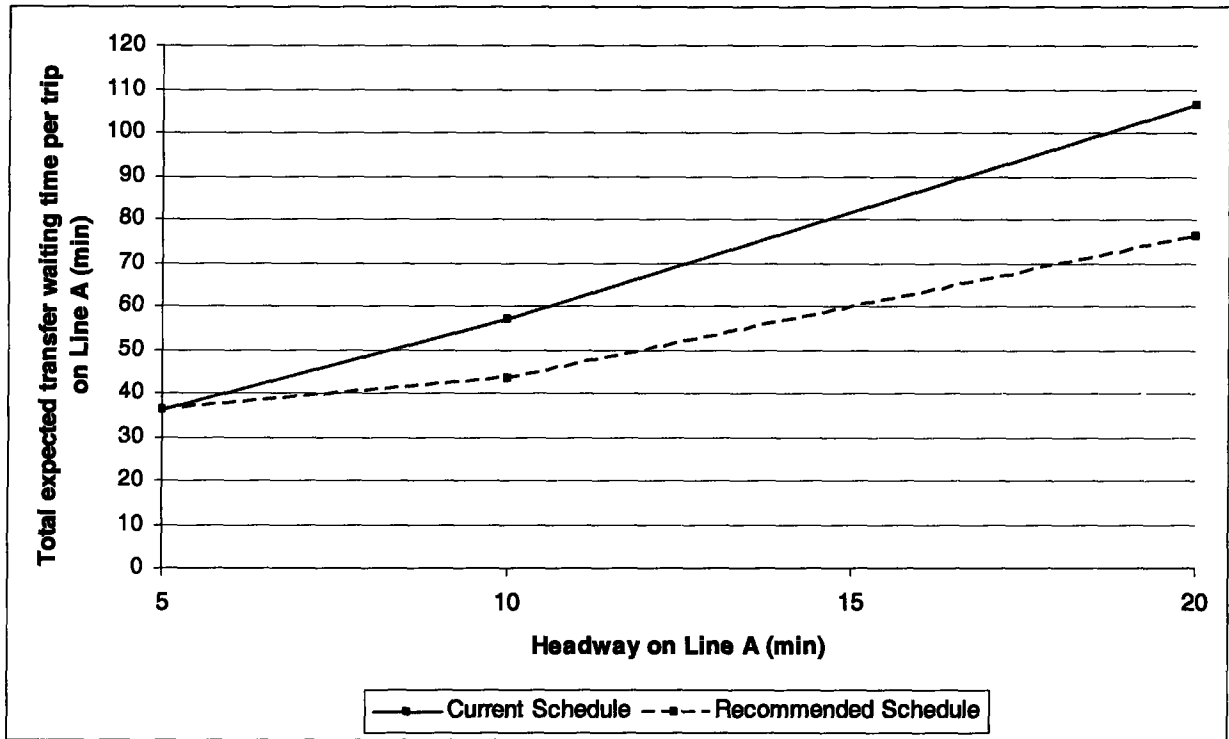
Influence of Vehicle Arrival Time Variance

Four scenarios (see Table 4-4) are investigated to test the effect of decreasing the vehicle arrival time variance on the results of the operations planning model. The results are summarized in Table 4-5 and the effect of each scenario on the change in the total expected transfer waiting time per trip on Line A is shown in Figure 4-4.

Table 4-4. Scenario Specifications

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Arrival Time Distribution	Line A	Triangular	Deterministic	Triangular	Deterministic
	Other Lines	Triangular	Triangular	Deterministic	Deterministic

Table 4-5. Sensitivity to Vehicle Arrival Time Variance

Scenario #	Offset Time (min)	Slack Time (min)	Expected Transfer Waiting Time per Trip on Line A (min)					
			T1 Passengers		T2 Passengers		All Passengers	
			C	R	C	R	C	R
1	4	0	20.8	14.4	36.4	29.0	57.1	43.5
2	4	0	21.8	12.5	37.9	26.9	59.7	39.4
3	4	0	21.8	12.5	37.8	26.8	59.6	39.3
4	5	0	18.0	13.0	45.0	20.0	63.0	33.0

C: current schedule, R: recommended schedule

Figure 4-4. Expected Benefits vs. Vehicle Arrival Time Variance
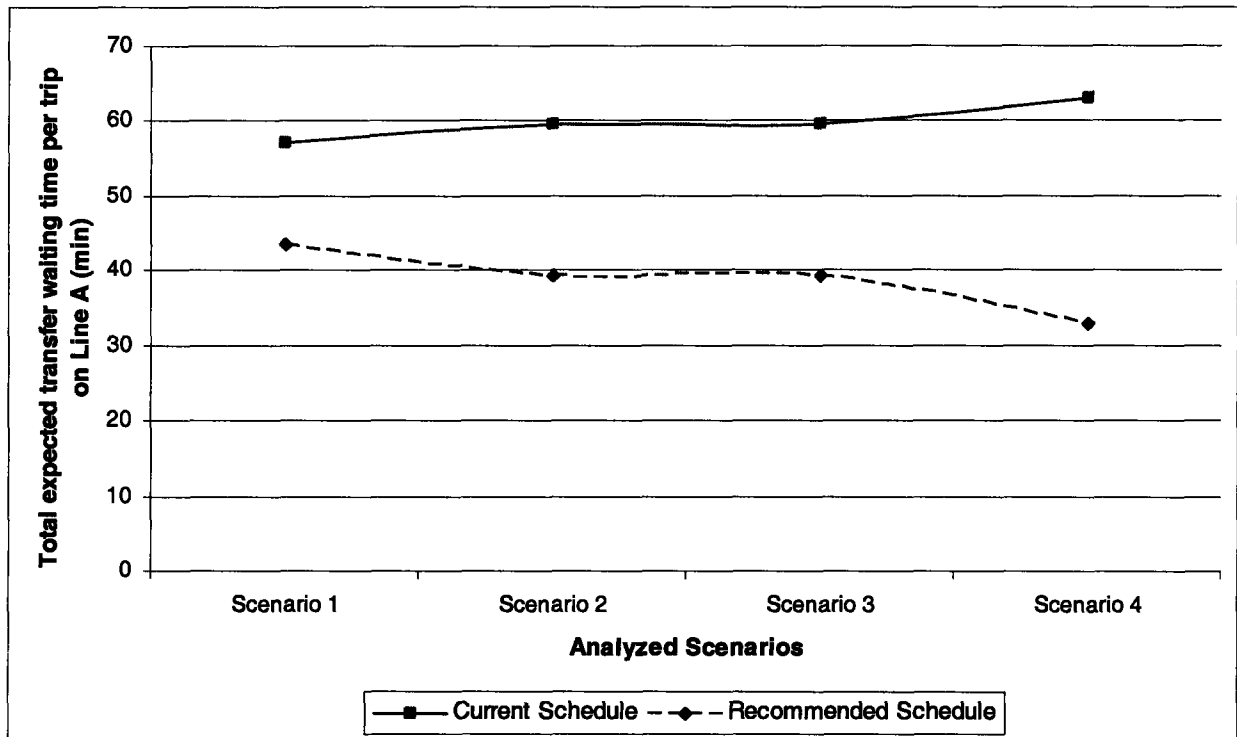
As expected, the benefits accruing from better scheduling increase as the variability in vehicle arrival times decreases. Changing the vehicle arrival time distributions either on Line A or on the

other connecting lines seems to have similar effects (Scenarios 2 and 3). Both lead to a 34% reduction in the total expected transfer waiting time per trip on Line A. This percentage reduction increases to 48% when the vehicle arrival times of all the lines in the system are deterministic (Scenario 4). Only in this scenario does the planning model recommend dispatching all vehicles on Line A five minutes later from the terminal. This allows for the maximum number of good connections to be completed in this case. If vehicles on Line A were dispatched four minutes (instead of five minutes) later in scenario 4, transfer coordination would still lead to substantial benefits in the form of a 46% reduction in the total expected transfer waiting time. The percentage reductions in total expected transfer waiting time are thus very close for both four and five minute offset times. This implies that the timetable recommended by the operations planning model is quite robust and does not change significantly with different levels of variability in vehicle arrival times.

For each scenario, the optimal slack times suggested by the model are equal to zero. Therefore, optimal slack times at stops 3 and 5 are not sensitive to the vehicle arrival time variance under the baseline conditions. It appears that, at low transfer demands, adding slack time to the schedule of Line A can not be justified even if the headway on that line is long or the vehicle arrival times of all connecting lines are deterministic.

Influence of Transfer Demand to Line A at Stop 5

In the baseline case, the number of passengers transferring to Line A are three at stop 5. These relatively low volumes are now increased to study the effect on the suggested operation plan. Results (see Table 4-6) show that the recommended service timetable does not change as the transfer demand increases. Consequently, all vehicles on Line A are still dispatched four minutes later from the starting terminal with no slack time added in their schedule at the different timepoints along the route.

The reduction in the expected transfer waiting time of T2 passengers is unaffected by this increase in transfer demand to Line A because the same optimal schedule is maintained. T2 passengers experience time savings amounting to approximately 21%. On the other hand, the reduction in the expected transfer waiting time of T1 passengers increases linearly with the increase in the number of those passengers. This leads to a linear increase in the overall benefits accruing from transfer coordination as the number of passengers transferring to Line A at stop 5 increases as shown in Figure 4-5.

Table 4-6. Sensitivity to Transfer Demand to Line A at Stop 5

Transfer Volume (pax/trip on Line A)	Offset Time (min)	Slack Time (min)	Expected Transfer Waiting Time per Trip on Line A (min)					
			T1 Passengers		T2 Passengers		All Passengers	
			C	R	C	R	C	R
3	4	0	20.8	14.4	36.4	29.0	57.1	43.5
6	4	0	36.9	24.8	36.4	29.0	73.2	53.9
9	4	0	53.0	35.2	36.4	29.0	89.4	64.2
12	4	0	69.1	45.6	36.4	29.0	105.5	74.6
15	4	0	85.3	56.0	36.4	29.0	121.6	85.0
18	4	0	101.4	66.4	36.4	29.0	137.8	95.4
21	4	0	117.5	76.7	36.4	29.0	153.9	105.8
24	4	0	133.6	87.1	36.4	29.0	170.0	116.2
27	4	0	149.8	97.5	36.4	29.0	186.1	126.5
30	4	0	165.9	107.9	36.4	29.0	202.3	136.9

C: current schedule, R: recommended schedule

Figure 4-5. Expected Benefits vs. Transfer Volumes to Line A at Stop 5
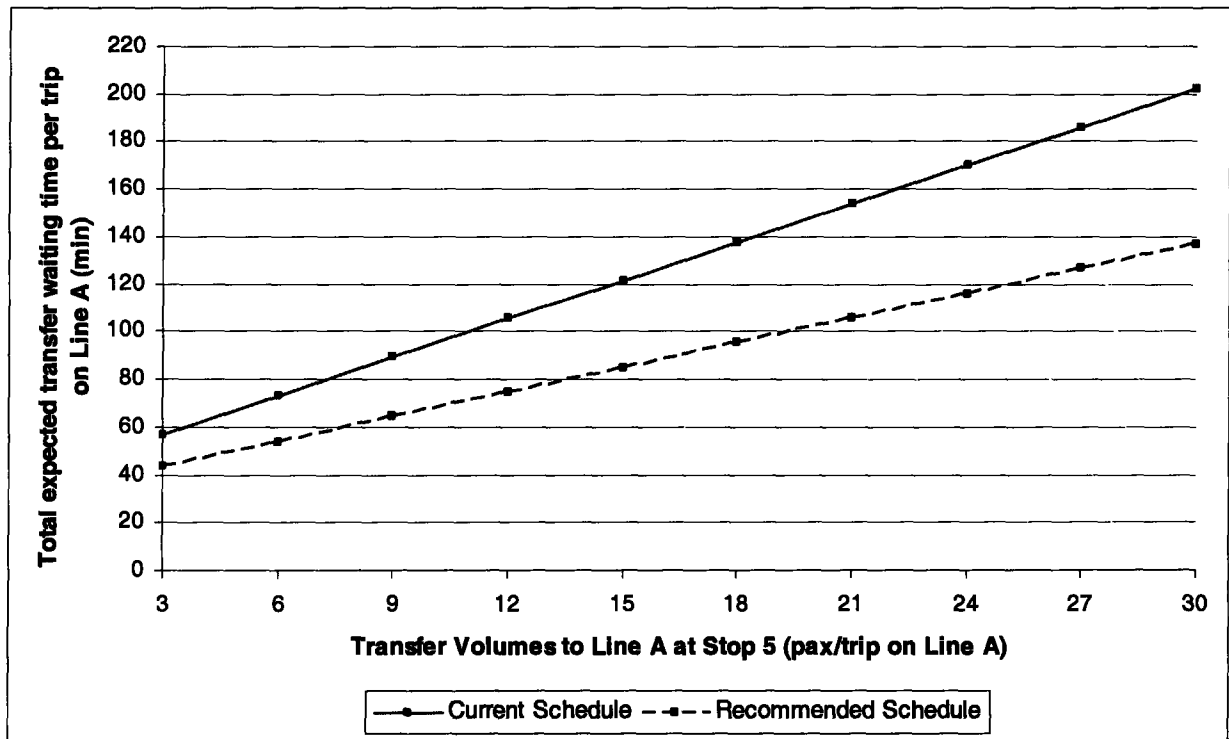
Influence of Passenger Time Values

Changing the time ratios in the range 1 – 2 has no effect on the recommended timetable. This is expected since slack will never be added in the schedule of Line A due to the combination of low ratio of the number of transferring passengers to Line A to the number of through passengers at the transfer stops and the high frequency on Line A. Since the same schedule is maintained, the reduction in the expected waiting time for both T1 and T2 passengers – and consequently for all passengers – remains unchanged.

4.3 OPERATIONS CONTROL MODEL APPLICATION

This section covers the application of the operations control model to stop 5 on Line A. The aim is to evaluate holding decisions at that stop and to suggest holding guidelines based upon the net passenger-minutes saved in the course of improving transfers. The base scenario results are first discussed followed by an assessment of the sensitivity of these results to different values for headways, transfer volumes and time ratios.

4.3.1   Base Scenario

The operations control model is applied to stop 5 under the baseline conditions presented in Section 4.1. This stop is selected because it experiences the highest number of transfer movements to Line A (3 passengers/trip on Line A) and the lowest number of through passengers on that line (18 passengers/trip on Line A). Vehicle holding will be more likely to be justified at this stop than at stop 3. For the base scenario, the control strategy is applied independent of the proposed operations plan to better illustrate the implications of each on network operations. Consequently, the current timetable is adopted and the maximum available holding time is assumed equal to five minutes. Additionally, passengers are assumed to arrive at all the stops at a constant rate of 0.5 passengers per minute, which is representative of transfer stops on CTA routes.

For any vehicle which is ready to be dispatched from stop 5 on Line A, the question is whether to dispatch it immediately or to hold it for an arriving vehicle with connecting passengers. This holding assessment is based upon the net passenger-minutes saved both for transferring and non-transferring passengers. Holding benefits those passengers transferring to Line A at stop 5 (P1), delays through passengers at that stop (P2), inconveniences passengers already waiting at that stop and at downstream stop 6 (P3), and saves time for passengers arriving at stops 5 and 6 during the holding period (P4).

Five hundred runs were carried out for the base scenario. The results presented are average values taken over all these runs. The operations control model suggests that a vehicle arriving at stop 5 on Line A has a 28% probability of being held for an incoming vehicle on a connecting line. This is assuming that the minimum holding threshold set by the transit agency is zero passenger minutes i.e. the only criterion for holding is that there be net passenger-minutes saved. As the minimum holding threshold increases, the holding probability decreases as shown in Figure 4-6. This is expected and agrees with the findings of Wong [2000] who showed that increasing the minimum holding threshold results in fewer but more substantial holds. For a minimum holding threshold greater than fifteen passenger-minutes, the probability of holding a vehicle at stop 5 on Line A approaches zero. The combination of low transfer demand to Line A at that stop and short headway on that line result in a small missed connection cost that can not justify holding a vehicle if such an action must produce significant benefits.

Figure 4-6. Probability of Holding a Vehicle at Stop 5 on Line A
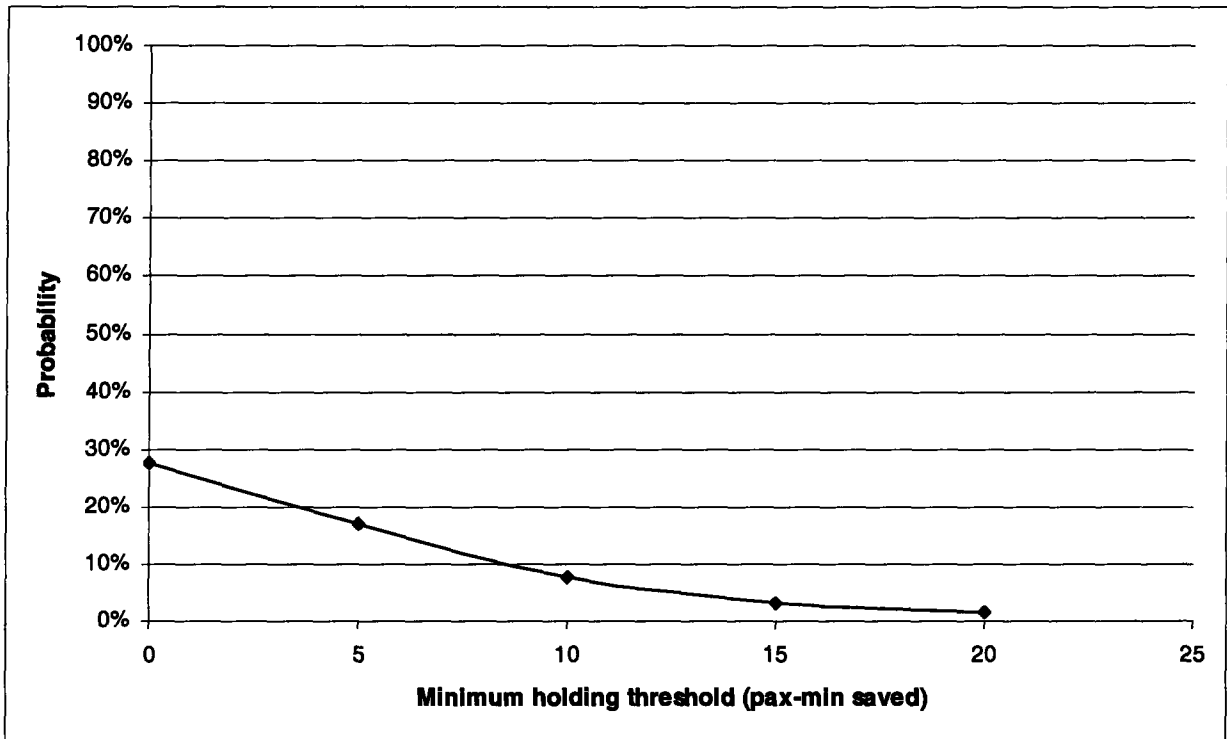
Figure 4-7 shows the conditional probability of holding a vehicle – which is ready to be dispatched from stop 5 on Line A – given a particular required holding time, x, and a minimum holding threshold, y. In other words if the transfer process can be completed successfully in x minutes, the figure shows the probability that a "ready" vehicle at stop 5 on Line A is held for these x minutes knowing that a hold is only appropriate if it results in net passenger-minute savings of at least y minutes. For any minimum holding threshold, Figure 4-7 shows that a "ready" vehicle at stop 5 on Line A should be considered for holding only if the required holding time needed to allow transferring passengers to complete their connection is less than or equal to two minutes. Since the minimum connection time assumed for this application is two minutes, holding a "ready" vehicle can thus be considered an option only if the connecting vehicle has arrived and the connecting passengers have already started the transfer process. Otherwise, the "ready" vehicle should be dispatched immediately.

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Figure 4-7. Conditional Probability of Holding a Vehicle at Stop 5 on Line A given a Required Holding Time and a Minimum Holding Threshold
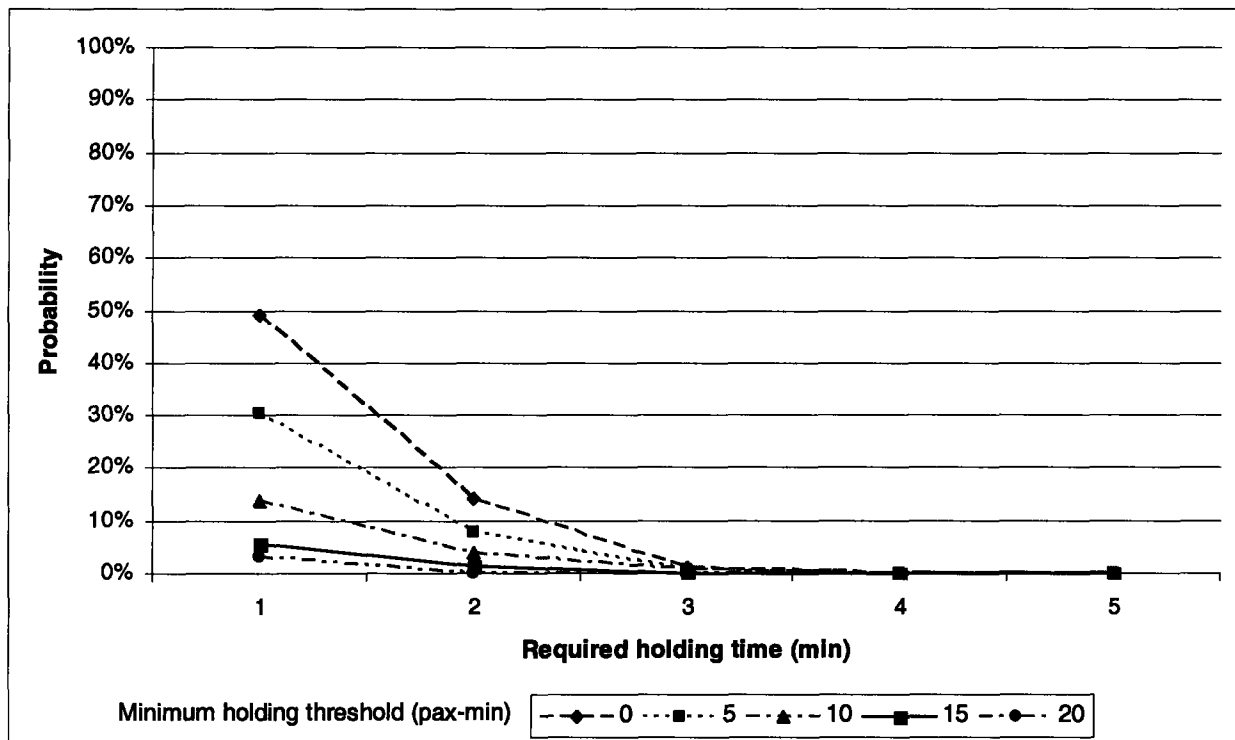
For a particular minimum holding threshold, the probability of holding a "ready" vehicle decreases as the required holding time increases. This is expected because the longer the holding time, the greater the delays experienced by P2 and P3 passengers relative to the benefits accrued by P1 and P4 passengers and hence the lower the net passenger-minutes saved. Moreover, as the minimum holding threshold increases, the holding probability decreases for any required holding time. At a minimum holding threshold of twenty passenger-minutes, a "ready" vehicle at stop 5 is almost always dispatched immediately regardless of the position of the closest connecting vehicle. As explained earlier, this is due to a combination of the low number of transferring passengers relative to the number of through passengers and the frequent service on Line A which result in a small missed connection cost.

Throughout the remainder of this section, the minimum holding threshold will be set at zero passenger-minutes. At such a threshold, if the transferring passengers require only one minute to complete their connection successfully (i.e. required holding time is one minute), the operations control model shows that the probability of holding a "ready" vehicle is 50% (see Figure 4-7). To better identify these instances when holding is beneficial, certain operating

factors must be considered. Key factors which affect the net time savings are the preceding headway and the following headway on Line A. The preceding headway on Line A affects the number of P2 and P3 passengers. The shorter this headway, the fewer the number of adversely affected passengers. The following headway on Line A affects the expected waiting time incurred by P1 and P4 passengers if they miss their connection and limits the duration of a hold. The longer this headway, the more the time savings accrued by P1 and P4 passengers. As such, the greatest benefits from holding occur when the preceding headway on the destination line is short and the following headway on that line is long.

Figure 4-8 shows the conditional probability of holding a "ready" vehicle at stop 5 on Line A given a required holding time and a particular combination of preceding and following headways on that line (see Table 4-7).

Table 4-7. Combination Specifications

	Comb 1	Comb 2	Comb 3	Comb 4	Comb 5	Comb 6
Preceding Headway	< 8 min	< 8 min	8 – 12 min	8 – 12 min	> 12 min	> 12 min
Following Headway	< 10 min	>= 10 min	< 10 min	>= 10 min	< 10 min	>= 10 min

The figure shows that if the required holding time is one minute, a "ready" vehicle is almost always held at stop 5 (90 - 95% of the time) if its preceding headway is less than eight minutes regardless of its following headway. If its preceding headway is between eight and twelve minutes, the conditional probability of holding that vehicle is reduced substantially to about 55%. This probability is reduced even further, to about 15%, if the preceding headway is greater than twelve minutes. For a required holding time of one minute, the conditional probability of holding a vehicle at stop 5 therefore decreases as the preceding headway on Line A increases. The associated higher passenger demand results in a greater number of P2 and P3 passengers who will be delayed by holding. The additional delay incurred by these passengers usually outweighs the time saved by benefiting passengers and minimizes the potential of a beneficial hold.

This observation is also true if the required holding time is two minutes, but in this case the outcome also depends on the following headway. A "ready" vehicle is held approximately 67%

of the time if its preceding and following headways fall in combination 2. First, this vehicle will have fewer through passengers as well as fewer boarders who have accumulated since the previous vehicle. Second, the transferring passengers, as well as those boarding during the hold, will save more time given the long following headway (>= 10 minutes). However if this following headway is less than ten minutes (i.e. combination 1), the conditional probability of a hold being beneficial drops to 43%. In summary, Figure 4-8 shows that the scenario under which real-time operation intervention produces the most significant benefits is when a vehicle arrives with a short preceding headway and a long following headway.

Figure 4-8. Conditional Probability of Holding a Vehicle at Stop 5 on Line A given a Required Holding Time and a Particular Preceding and Following Headway Combination
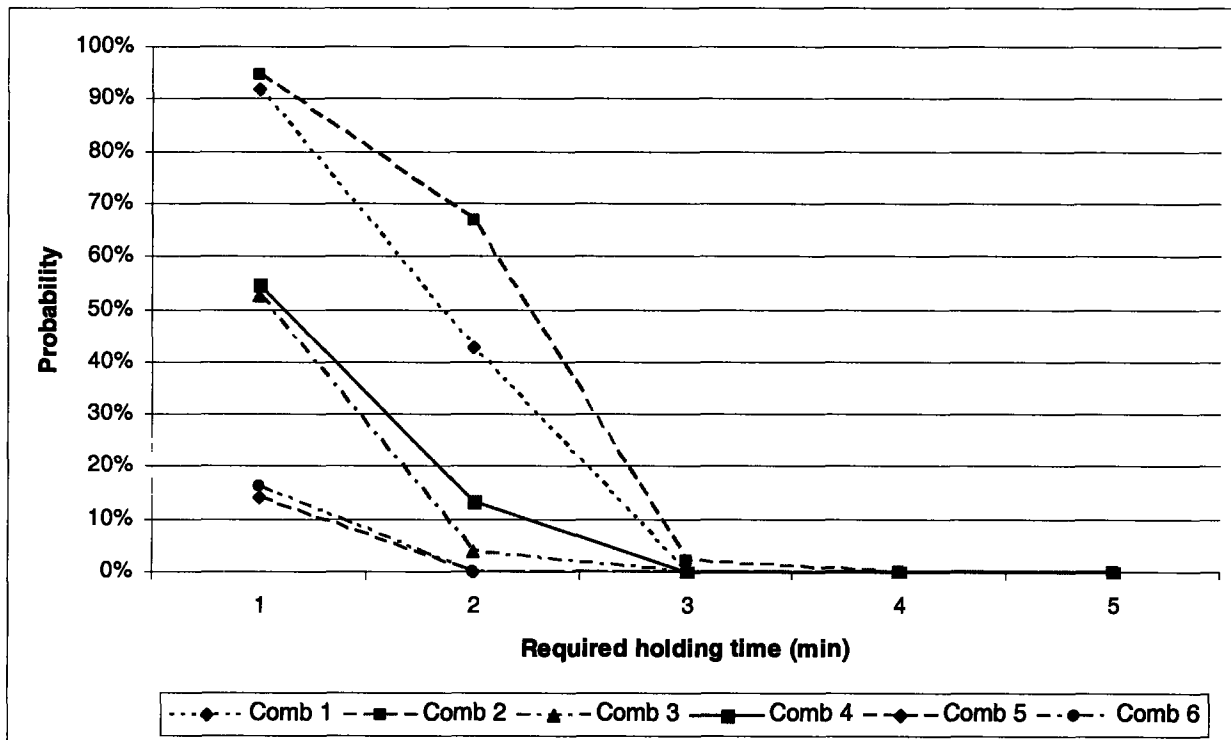
4.3.2   Further Analysis

This section presents the results from the application of the operations control model when the headway on Line A, transfer volumes to Line A, and passenger time values are varied. The aim is to investigate the sensitivity of holding to these factors.

Influence of Headway on Line A

The headway on Line A is varied from 5 minutes to 30 minutes in 5-minute increments to investigate the impact on the potential for holding a vehicle at stop 5 with all the other baseline parameters assumed the same. Figure 4-9 shows the probability of holding a "ready" vehicle at stop 5 on Line A for the different line headways. The figure shows that the probability of vehicle holding increases modestly with the scheduled line headway. This is expected since longer headways imply longer waiting times, which in turn imply greater missed connection costs. However, even at scheduled headways of thirty minutes, the probability of a hold being beneficial is not very high (39%). This is mainly a result of the low transfer demand to Line A at stop 5, which is the major driving factor behind any holding decision.

Figure 4-9. Probability of Holding a Vehicle at Stop 5 on Line A as a Function of Headway
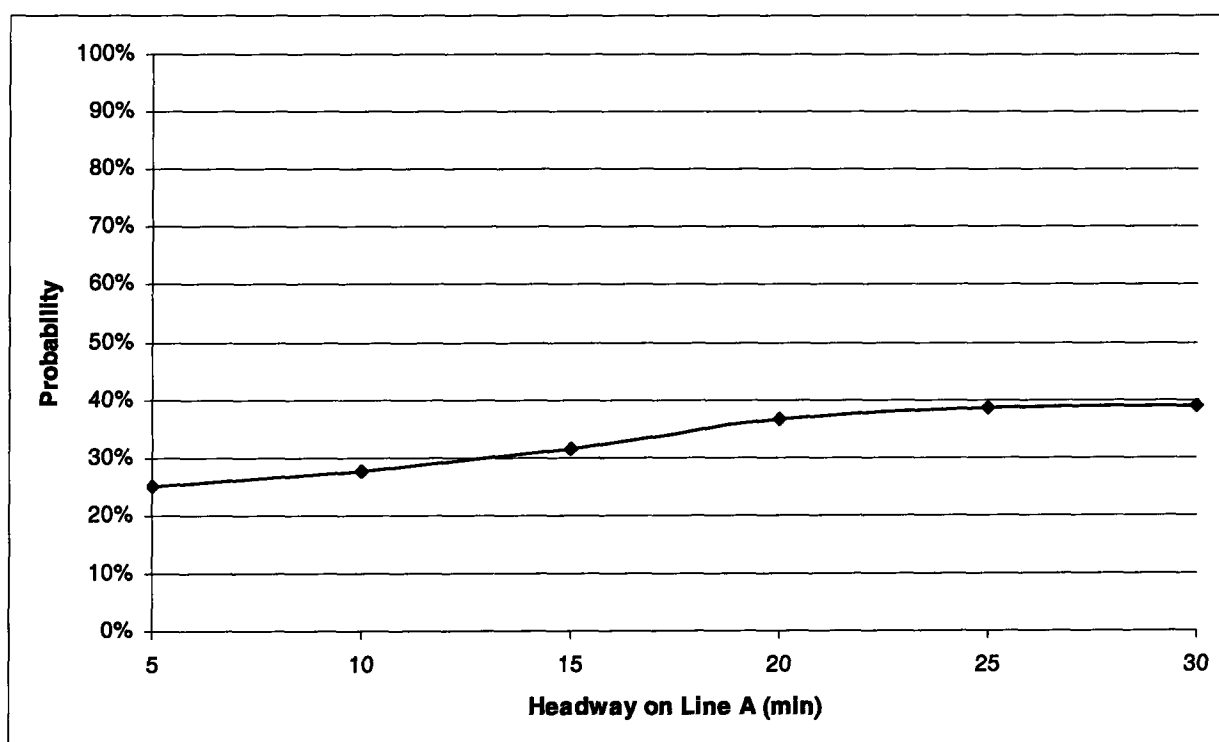
Figure 4-10 shows the conditional probability of holding a "ready" vehicle given a particular required holding time and scheduled line headway. The trends in this figure are consistent with the general trend in Figure 4-9: as the scheduled line headway increases, so does the conditional probability, albeit modestly. Still, if an incoming connecting vehicle is more than a minute away from stop 5 (i.e. required holding time is greater than three minutes), the "ready"

vehicle should always be dispatched immediately. Even with long headways, it is ineffective to hold a vehicle for four or five minutes due to the low transfer demand to Line A at that stop.

Figure 4-10. Conditional Probability of Holding a Vehicle at Stop 5 on Line A given a Required Holding Time and a Scheduled Line Headway
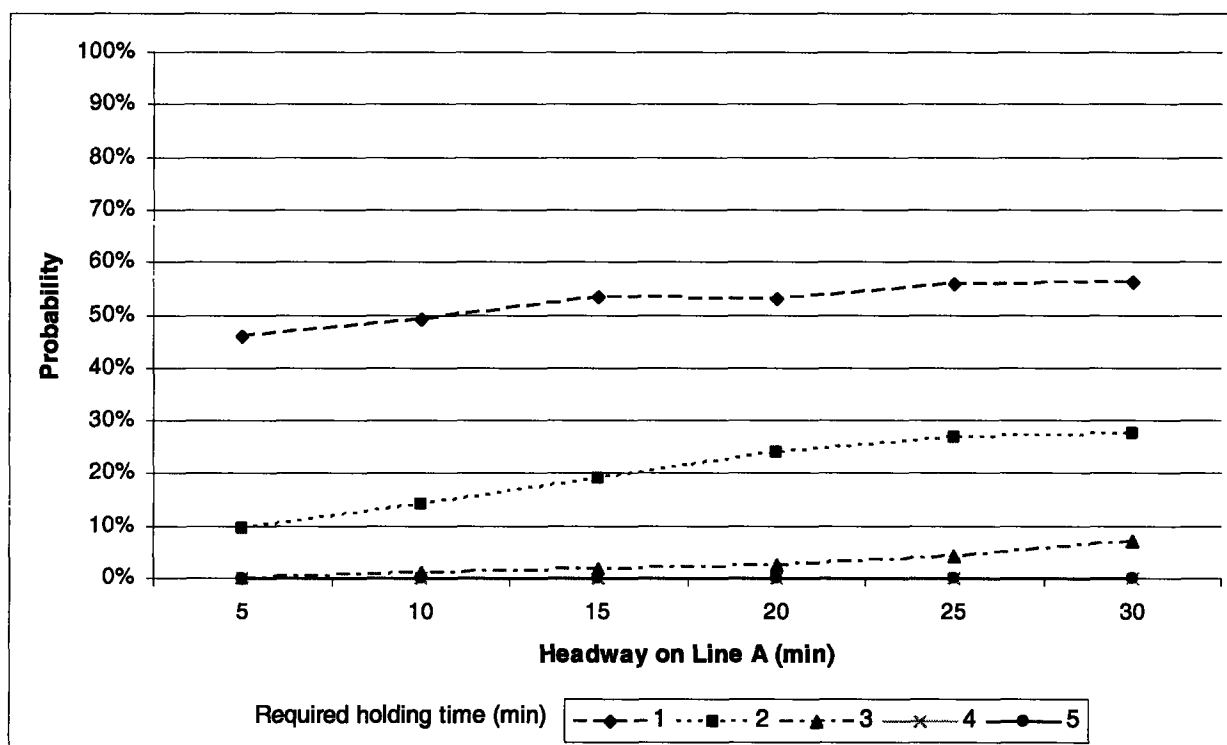
Influence of Transfer Demand to Line A

The number of passengers transferring to Line A at stop 5 are now increased to study the effect on holding. Figure 4-11 shows that the probability of holding a "ready" vehicle increases with increasing transfer volume. When the number of P1 passengers increases, their missed connection cost also increases and eventually becomes the major part of the total cost affecting the holding decision. Holding for transfers will minimize this missed connection cost and will lead to an overall improvement in system performance (i.e. positive net passenger-minutes saved). The rise in holding probability with increasing transfer demand is quite rapid and approaches 100% when the ratio of the number of transferring passengers to Line A at stop 5 to the number of through passengers at that stop is greater than 1.3. At such high transfer volumes, almost all vehicles arriving at stop 5 on Line A are thus held for incoming vehicles from connecting lines. This is due to the current timetables on Lines A, D and E. These schedules

lead to required holding times which are less than three minutes 95% of the time. Holding a "ready" vehicle for such a short time benefits the large numbers of transferring passengers and results in only small delays to through passengers.

Figure 4-11.Probability of Holding a Vehicle at Stop 5 on Line A
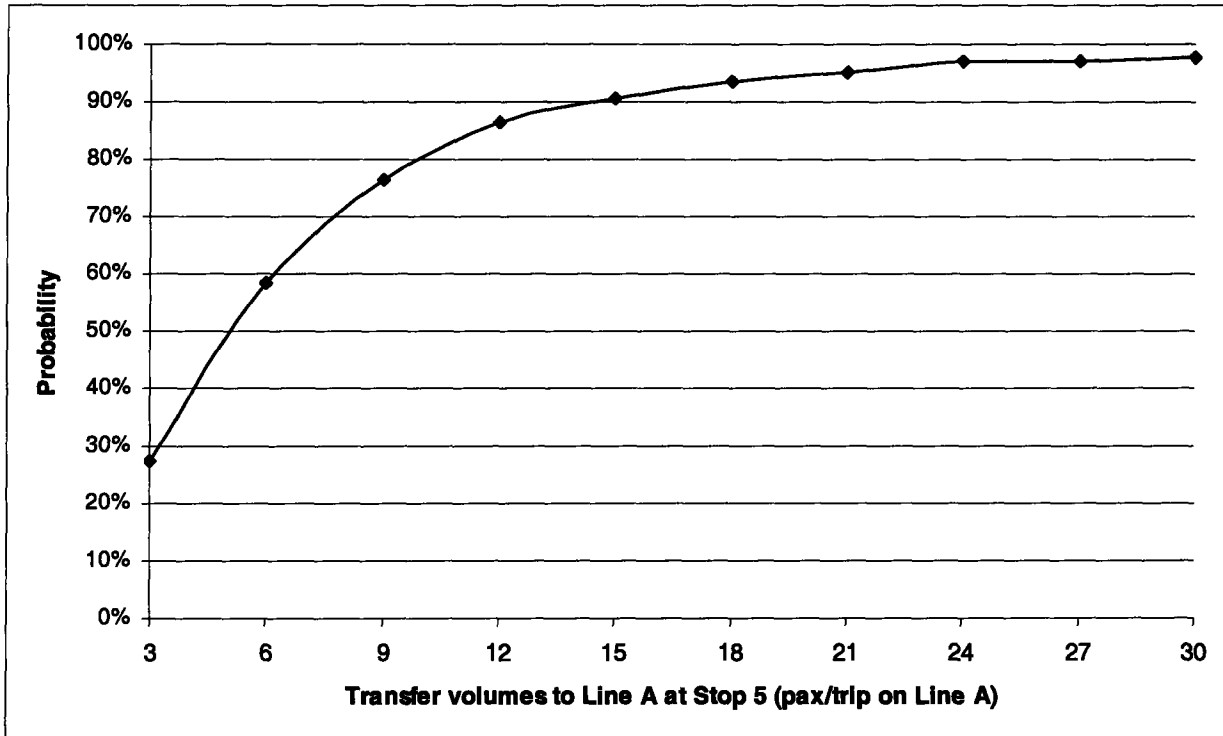
Figure 4-12 shows the conditional probability of holding a "ready" vehicle given a required holding time and a particular transfer demand to Line A at stop 5. At transfer volumes which are three times the base scenario, each "ready" vehicle at stop 5 should be held for transferring passengers from an incoming connecting vehicle if the required holding time is one minute. If the required holding time is two or three minutes, then a "ready" vehicle should always be held if the number of connecting passengers is at least 24 (i.e. 30% more than the number of through passengers). Figure 4-12 also shows that there are some instances in which it is beneficial to hold the "ready" vehicle at stop 5 for four or even five minutes. Holding a vehicle for such a long duration may be viable, even at a ten-minute headway, if the ratio of transferring passengers to through passengers is very high.

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Figure 4-12. Conditional Probability of Holding a Vehicle at Stop 5 on Line A given a Required Holding Time and Transfer Demand
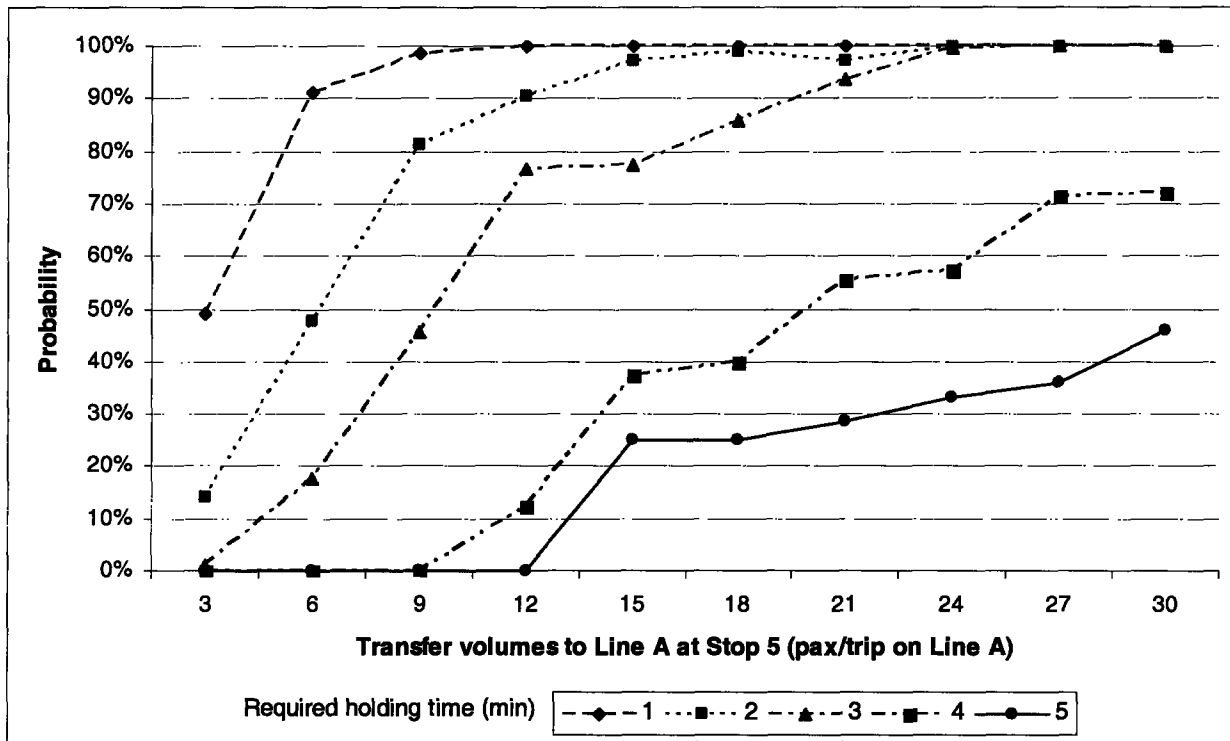
Influence of Passenger Time Values

The ratio of out-of-vehicle wait to in-vehicle delay is also varied to study its impact on control recommendations. It is hypothesized that lowering the time ratio will reduce the probability of holding. However, when out-of-vehicle wait is perceived to be twice as onerous as in-vehicle delay, the holding probability increases since more focus is now placed on transferring passengers' waiting time. These results are shown in Figure 4-13 below. The same general trend can also be observed for the conditional probabilities of holding a "ready" vehicle given a required holding time and a particular time ratio as shown in Figure 4-14.

Figure 4-13. Probability of Holding a Vehicle at Stop 5 on Line A
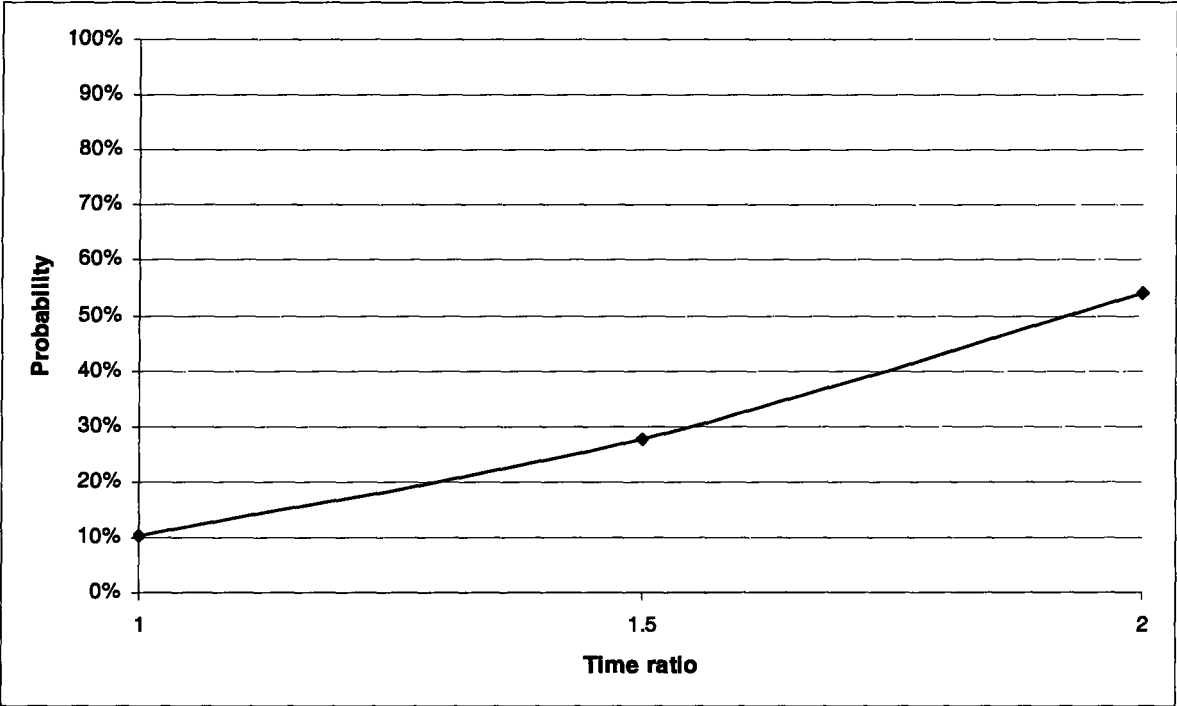
Figure 4-14. Conditional Probability of Holding a Vehicle at Stop 5 on Line A given a Required Holding Time and Time Ratio
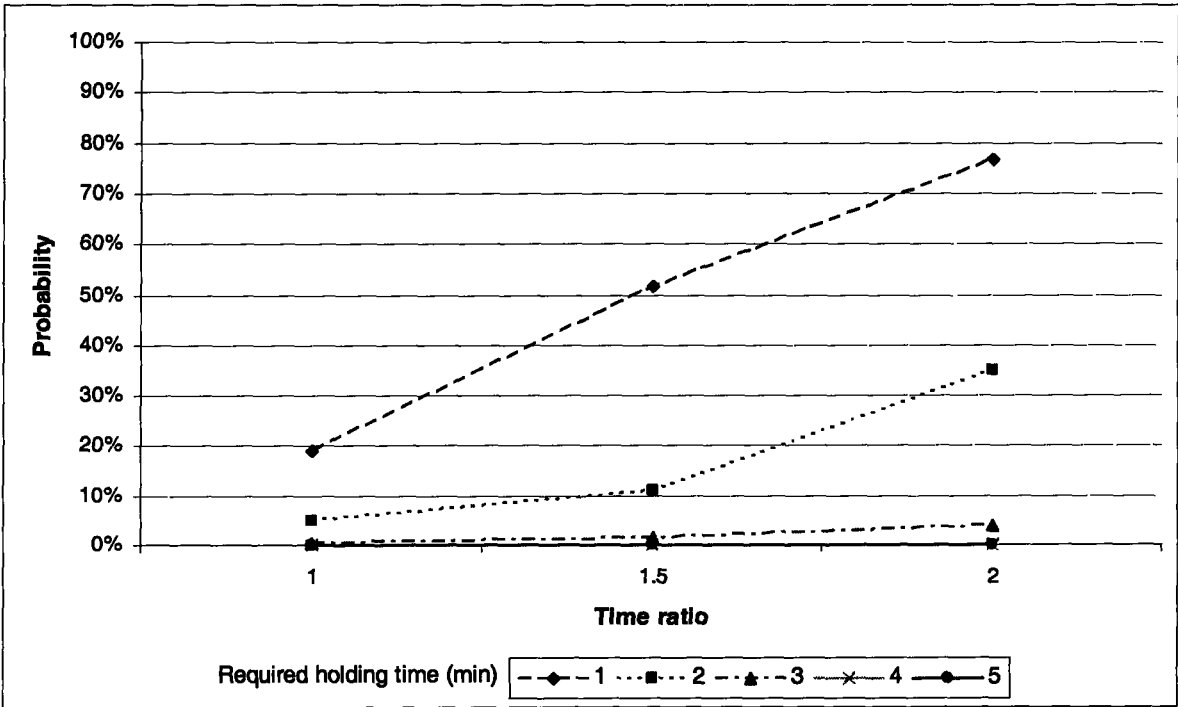
Influence of Proposed Service Timetable

The service timetable suggested by the operations planning model in Section 4.2.1 was also analyzed to study the impact of adopting a sequential approach to transfer coordination which involves optimizing offset and slack times beforehand. (Recall from that section that the optimal offset time is four minutes and the optimal slack times at stops 3 and 5 are zero minutes.) Under such a timetable, a "ready" vehicle at stop 5 on Line A is dispatched immediately 91.8% of the time because its expected departure time from that stop now allows for transferring passengers from incoming vehicles on both connecting lines to complete their connection. The probability of holding any vehicle is now only 6.6%. For the cases where holding is beneficial, the required holding time is only one minute. There are no instances when a "ready" vehicle needs to be held for a longer time.

5   APPLICATION TO CTA

This chapter applies the operations planning and control models to two corridors at the Chicago Transit Authority (CTA) system: Routes 53 and 63. The purpose is to recommend new service timetables and real-time holding decision rules, which will improve the transfer performance on both corridors. Section 5.1 presents the analysis of Route 53 and Section 5.2 presents that of Route 63. Within each section, the current route characteristics are first summarized. The operations planning model is then applied and its results discussed. Decision rules for the application of the control strategy at some transfer stops are also presented based on the results from Chapter 4.

5.1 ROUTE 53

This section presents the current conditions on Route 53 and the results of the application of the operations planning model to improve the transfer experience on that route. Some sensitivity analyses are also carried out and the corresponding outcomes are discussed and analyzed.

5.1.1   Route Characteristics

CTA Route 53, Pulaski, covers the north portion of Pulaski Street from Komensky (the southern terminal) to Peterson (the northern terminal). There are ten timepoints on this route including the two termini (see Figure 5-1) which allow the transit service schedule to be exactly specified indicating the earliest departure time of any vehicle. As discussed in Section 3.1, several factors led to the selection of the Pulaski route on weekdays and of the 10 am to noon time period for this case study. The following factors suggest that applying transfer coordination on this route in this time period has significant potential to generate benefits to transferring passengers:

Figure 5-1. CTA Route 53, Pulaski
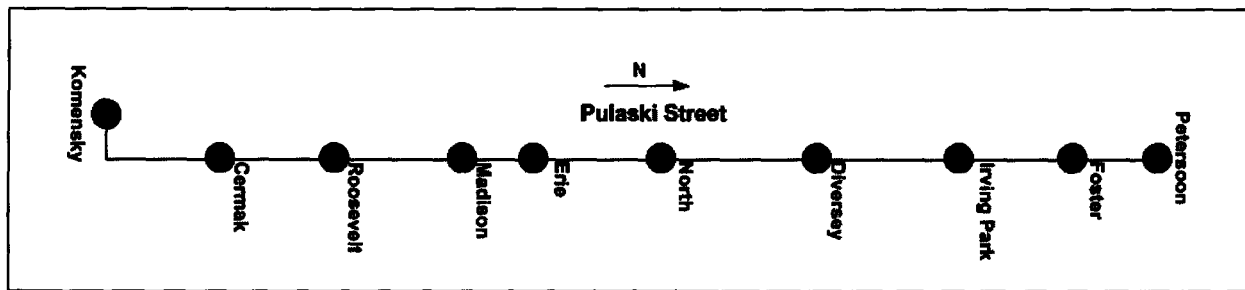
- During this time period, Route 53 connects with nineteen bus routes and four rail lines with an average of 1544 transferring passengers. Route 53 ranks six among the heaviest CTA routes in terms of total transfer activity, with the top route – Route 9 – having approximately 50% more transfers.

- The longer the expected wait for a transfer, the more the potential benefits from transfer coordination and so the average and standard deviation of the expected transfer waiting times are part of the corridor and time period selection process. As shown in the next section, the average expected waiting time per transferring passenger is currently 4.8 minutes at selected transfer stops between 10 am and noon.

- Headway compatibility plays an important role as well: if there are no connecting lines with headways compatible with Route 53, then the operations planning model can not be applied. Between 10 am and noon, the headway on Route 53 is ten minutes and a reasonable number of connecting lines have compatible headways (i.e. headways which are equal to or are a multiple of ten).

Finally, the ratio of transferring passengers to through passengers at each transfer stop along the corridor is also a key factor when making a selection. As noted in Section 3.1, transfer coordination is most beneficial when this ratio is high especially if the transfer activity is mostly concentrated at a few transfer stops. During the 10 am to noon period, the number of transferring passengers on Pulaski is divided almost equally among all transfer stops, with the directional transfer movements at each stop being one or zero passengers per trip in most cases. As such, the ratio of transferring passengers to through passengers is very low at almost all transfer stops. Although there should be benefits from coordinating transfers on Route 53, they might not be very significant.

Current Timetable

Table 5-1 shows the scheduled departure times of the first vehicle departing Komensky between 10 am and noon at the ten timepoints along the Pulaski route in both directions.

Table 5-1. Current Service Timetable on Route 53

Northbound Direction

Komensky	Cermak	Roosevelt	Madison	Erie	North	Diversey	Irving Park	Foster	Peterson
10:02	10:08	10:14	10:21	10:27	10:33	10:41	10:51	10:59	11:04

Southbound Direction

Peterson	Foster	Irving Park	Diversey	North	Erie	Madison	Roosevelt	Cermak	Komensky
11:11	11:15	11:22	11:32	11:42	11:48	11:54	12:01	12:07	12:13

The northbound half-cycle time is sixty-nine minutes including seven minutes of recovery time currently built-in at the Peterson terminal, and the southbound half-cycle time is seventy-two minutes including ten minutes of recovery time built-in at the Komensky terminal. Recovery times are usually set as a percentage – ranging from 10 to 20% - of the scheduled running times to ensure a desired on-time departure probability from the terminals. In the Pulaski case, recovery times are set at 11% and 16% of the scheduled running times in the northbound and southbound directions respectively.

5.1.2 Application of the Planning Model

The operations planning model developed in Chapter 3 is applied to Route 53 to improve its transfer performance. The selection of the transfer stops for analysis is presented in this section followed by the model inputs. The model results are presented and discussed in Section 5.1.3.

Selection of Transfer Stops

As discussed in Chapter 3, the transfer stops that are included in the application of the operations planning model must be timepoints and must have connecting lines with headways compatible with Route 53. The headway on Route 53 is ten minutes for the two-hour duration and Table 5-2 shows the headways of the different routes which connect with this route at its timepoints.

Table 5-2. Intersecting Route Headways

Rt. 53A	Rt. 21	Rt. 12	Rt. 20	Rt. 72	Rt. 76	Rt. 80	Rt. 92	Rt. 84
10 min	15 min	12 min	4 min	**10 min**	12 min	**10 min**	12 min	15 min

From Table 5-2, there are only three routes with compatible headways of ten minutes. These routes connect with Route 53 at the Komensky terminal and at the North and Irving Park timepoints as shown in Figure 5-2. As such, only three timepoints – out of ten – are included in this analysis.

Figure 5-2. Application of the Operations Planning Model
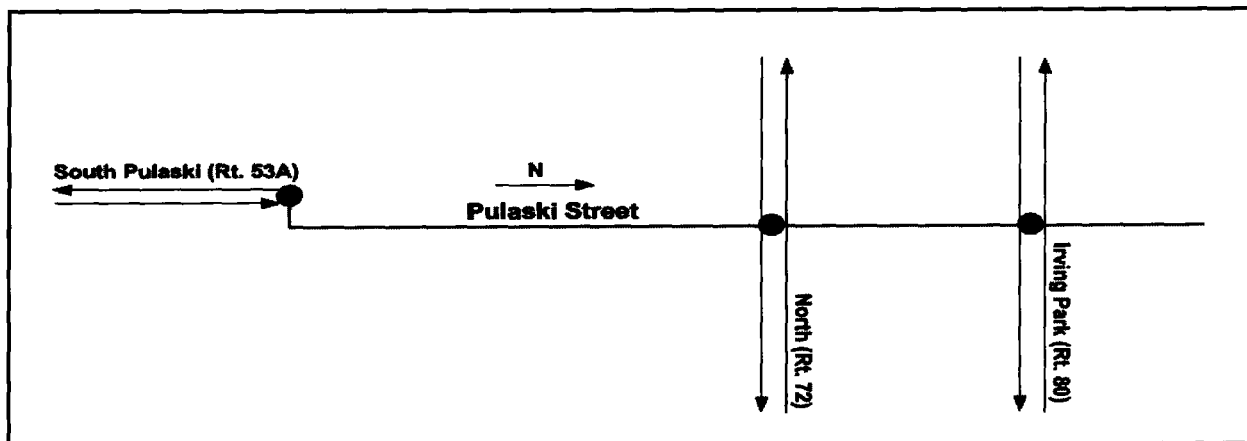
Model Inputs

The inputs to the operations planning model can be grouped into three distinct categories: arrival time distributions of the lines connecting at the selected transfer stops, through passenger and transfer passenger volumes on these intersecting lines, and other user-related parameters.

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1. Arrival Time Distributions

One of the strengths of the planning model is its ability to account for stochasticity in travel times. As discussed earlier, this model can accommodate any arrival time distribution input by the user. For this case study, the arrival time distributions of all the connecting lines at the selected transfer stops were obtained from the CTA Automatic Vehicle Location (AVL) System over a period of five days: January 12 - 16, 2004. Figure 5-3 shows a sample arrival time distribution at the North timepoint, on Route 53 (northbound). A negative deviation from schedule indicates an early arrival while a positive deviation indicates a late one. This distribution is based on data obtained from thirty-four runs that were recorded by the AVL system for this route over the five-day period. Although these runs total only about half the scheduled runs for those days (sixty-five scheduled runs), they are assumed to be representative and hence no modifications are made to this arrival time distribution. The arrival time distributions of all the connecting lines at the selected stops are calculated in a similar fashion and are summarized in Table 5-3.

Figure 5-3. Sample Arrival Time Distribution at the North timepoint on Route 53(northbound)
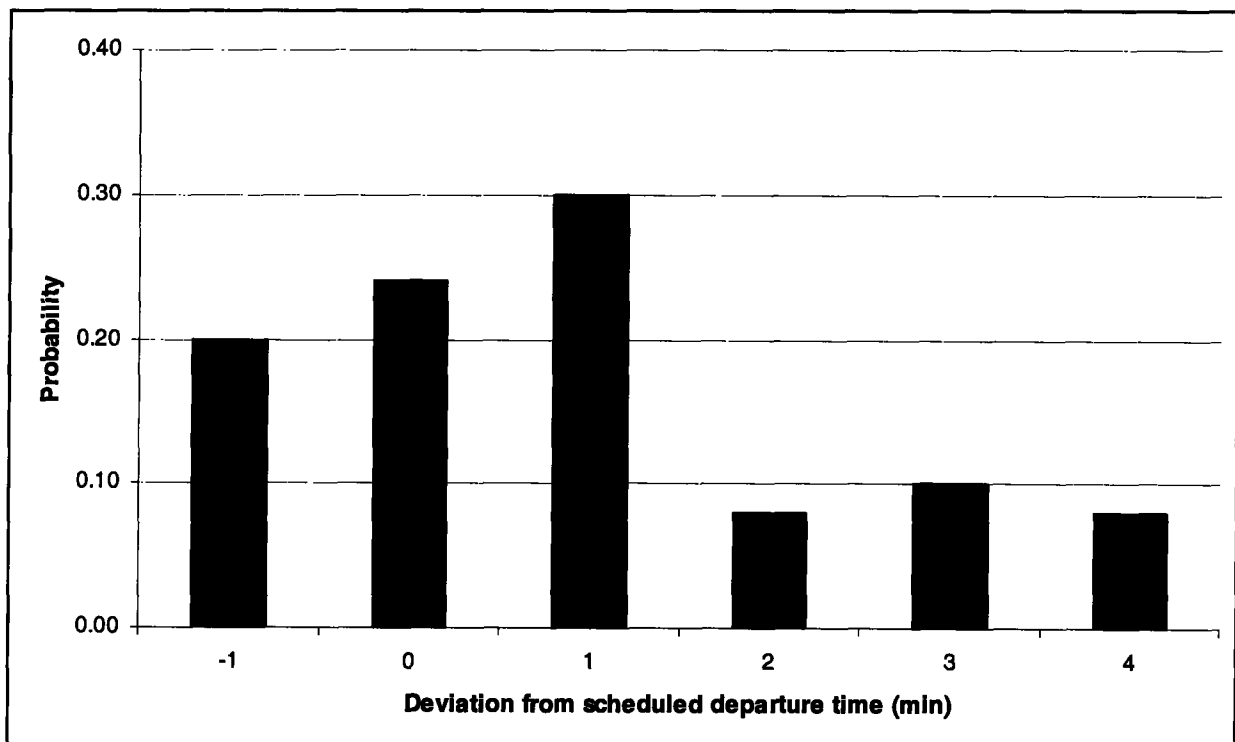
Table 5-3. Summary of Arrival Time Distributions of Connecting Routes at the Selected Timepoints

Komensky Terminal

Route	Direction	Scheduled Departure Time	Mean Deviation from Schedule	Standard Deviation	Minimum Deviation from Schedule	Maximum Deviation from Schedule
Pulaski (53)	Northbound	10:02	–	–	–	–
	Southbound	12:13	0.20 min	1.72 min	-2 min	3 min
South Pulaski (53A)	Northbound	10:05	-0.34 min	1.93 min	-4 min	2 min
	Southbound	10:04	–	–	–	–

North Timepoint

Route	Direction	Scheduled Departure Time	Mean Deviation from Schedule	Standard Deviation	Minimum Deviation from Schedule	Maximum Deviation from Schedule
Pulaski (53)	Northbound	10:33	0.88 min	1.49 min	-1 min	4 min
	Southbound	11:42	-0.49 min	2.08 min	-3 min	4 min
North (72)	Eastbound	10:30	-0.35 min	1.88 min	-3 min	3 min
	Westbound	10:33	0.67 min	2.09 min	-3 min	4 min

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Irving Park Timepoint

Route	Direction	Scheduled Departure Time	Mean Deviation from Schedule	Standard Deviation	Minimum Deviation from Schedule	Maximum Deviation from Schedule
Pulaski (53)	Northbound	10:51	0.11 min	1.94 min	-3 min	4 min
	Southbound	11:22	-0.10 min	2.19 min	-4 min	4 min
Irving Park (80)	Eastbound	10:48	-0.1 min	2.10 min	-4 min	4 min
	Westbound	10:45	0.89 min	2.40 min	-3 min	5 min

2. Passenger Demand

The application of a new service timetable potentially influences two categories of passengers: through passengers on Route 53 and transferring passengers between all selected connecting lines.

■ Through passenger volumes: passenger data were obtained from the CTA Automatic Passenger Counters (APC) System for the same five day period. This system records passenger boardings and alightings at each stop for each line with an operational APC System. The number of through passengers – as defined in the operations planning model context – is the difference between the number of passengers arriving at a stop on a particular line and the number of passengers alighting at that stop. Table 5-4 shows the average through passenger volumes on Route 53, northbound and southbound, at the transfer stops selected for analysis. These average values are based on only five runs (out of the total scheduled sixty-five runs) with APC data. As with the arrival time distributions, no modifications were made to these values since they were assumed representative.

Table 5-4. Average Through Passenger Volumes per Trip on Route 53

Pulaski (Northbound)		Pulaski (Southbound)	
North	*Irving Park*	*Irving Park*	*North*
23 pax	21 pax	21 pax	21 pax

- Transferring passenger volumes: transfer volumes were based on data obtained from the Automatic Fare Collection (AFC) System for September 2003. This system provides total monthly transfer volumes between all bus and rail routes in the CTA network, compiled in half-hour intervals for weekdays, Saturdays and Sundays/holidays. These volumes include 2nd and 3rd rides taken on a Transit, Chicago or Transfer Card and 2nd or 3rd rides taken on a pass/permit within 2 hours of the first ride. Average weekday transfer volumes for the time period under analysis (10 am to noon) are easily calculated from the AFC System for the connecting routes at the selected timepoints. These average volumes, however, are not directional. They only represent the transfers between two routes; no volumes are readily available for transfers between two lines – which is the input needed for the operations planning model. (Recall that a line is defined as the directional route between the terminals).

To estimate transfer volumes by direction, we assumed that transfer movements are proportional to passenger flow, where average boardings and alightings at any stop can be easily obtained from the APC System. Consider two routes, X and Y, with passengers transferring from X to Y at a particular transfer stop. Let T_A (T_B) be the number of passengers transferring from line A (B) of X to Y and A_A (A_B) be the number of passengers alighting from line A (B) at the transfer stop. Our assumption is:

$$\frac{T_A}{T_B} \equiv \frac{A_A}{A_B} \qquad \textbf{\textit{Equation 5-1}}$$

Similarly, the ratio of passengers transferring to the two directions of route Y is equivalent to the ratio of passengers boarding in these directions at the transfer stop. The process of obtaining such directional transfer movements from non-directional transfer volumes is illustrated through the use of an example, transfers between North and Pulaski. This process involves four steps:

- The average transfer volume from Route 72 to Route 53 at Pulaski is 4 passengers/trip for weekdays between 10 am and noon. This number is based on data from the AFC System.

- The number of passengers transferring from the North (eastbound) and North (westbound) lines to Pulaski is obtained assuming it is proportional to the number of passengers alighting from the North (eastbound) and North (westbound) lines at Pulaksi respectively. Figure 5-4 shows the average alightings per trip on the North route at Pulaski. These average numbers are obtained from data recorded by the APC system for the five-day period. They show that of the total number of passengers alighting from the North route at Pulaski, on average 36% alight eastbound and 64% alight westbound. As a result, we assume that 36% of the passengers transferring from North to Pulaski originate eastbound and the remaining 64% originate westbound.

Figure 5-4. Average Alightings per Trip on North at Pulaski
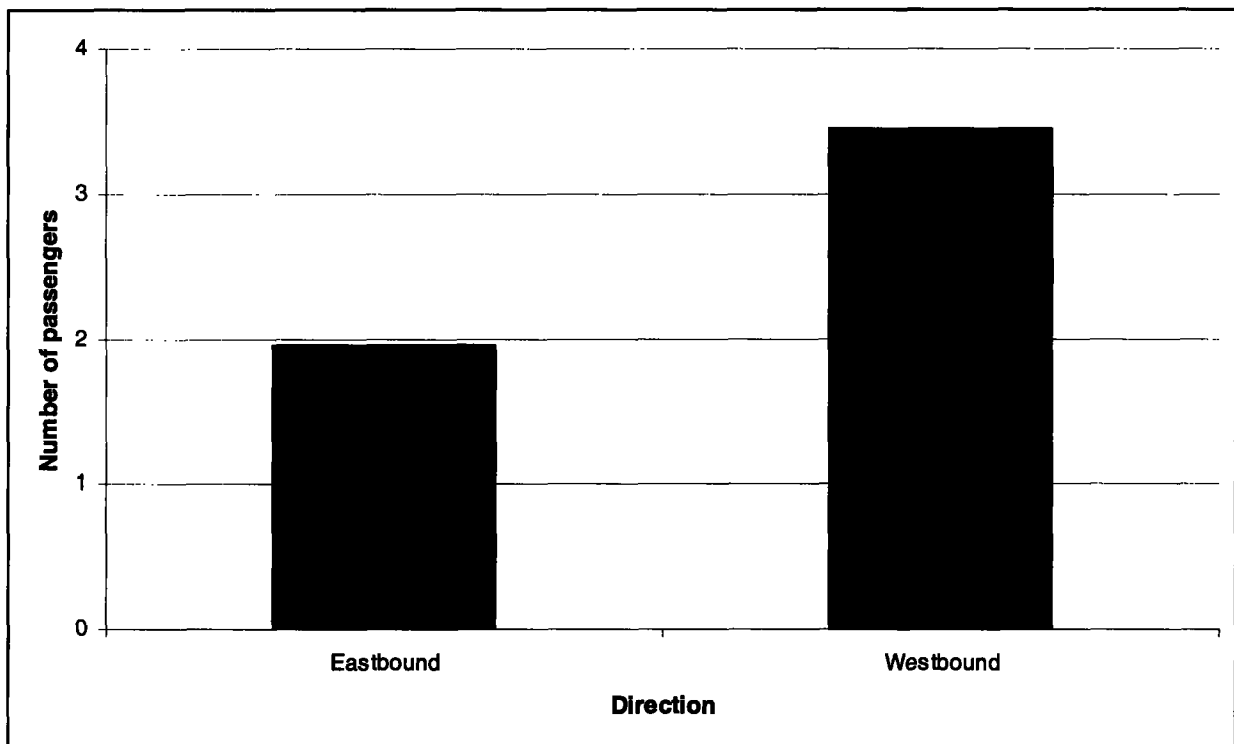
- The number of passengers transferring from North to the Pulaski (northbound) and Pulaski (southbound) lines is now obtained assuming it is proportional to the number of passengers boarding the Pulaski (northbound) and Pulaski (southbound) lines at North respectively. Figure 5-5 shows the average boardings per trip (from the APC System) on the Pulaski route at North. They show that of the total number of passengers boarding the Pulaski route at that stop, 33% board northbound and 67% board southbound. As a result, we assume that 33% of the passengers transferring from North to Pulaski head northbound and the remaining 67% head southbound.

Figure 5-5. Average Boardings per Trip on Pulaski at North
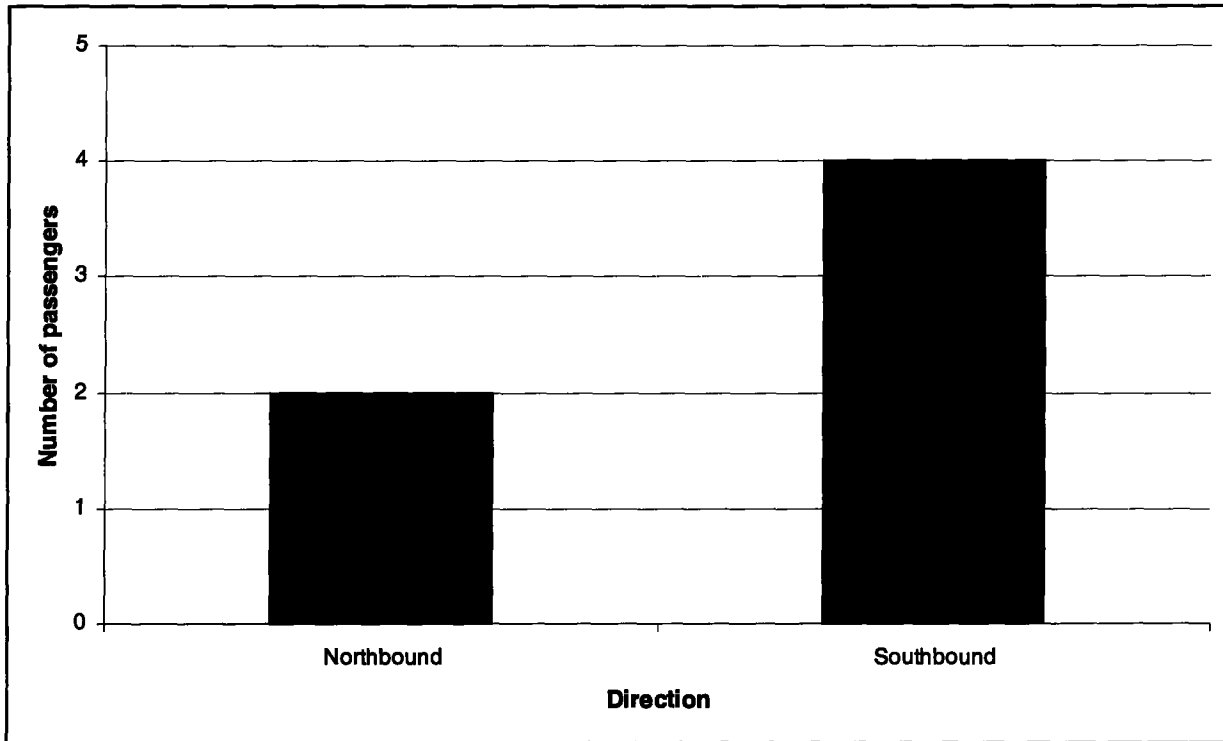
- The final step involves the calculation of the average number of passengers transferring per trip from North to Pulaski by direction. The results are shown in Table 5-5. The same process is applied to get the directional transfer movements between all the lines connecting at the selected transfer stops along the Pulaski corridor as shown in Table 5-6.

The total transfer activity at the three transfer stops considered on the Pulaski corridor is 20 passengers/trip out of a total of 129 passengers/trip if all transfer stops on the corridor are considered.

Table 5-5. Calculation of Directional Transfer Volumes from North to Pulaski

	Pulaski Northbound	Pulaski Southbound
North Eastbound	= 0.36*0.33*4 = 0	= 0.36*0.67*4 = 1
North Westbound	= 0.64*0.33*4 = 1	= 0.64*0.67*4 = 2

Table 5-6. Directional Transfer Movements between All Connecting Routes (pax/trip)

From \ To	S.Pul (N)	S.Pul (S)	Nor (E)	Nor (W)	Irv (E)	Irv (W)
Pul (N)	–	–	1	1	2	1
Pul (S)	–	3	1	1	–	–

To \ From	S.Pul (N)	S.Pul (S)	Nor (E)	Nor (W)	Irv (E)	Irv (W)
Pul (N)	4	–	–	1	–	–
Pul (S)	–	–	1	2	1	1

3. User-related Parameters

- Offset range: this is the time window within which the current departure time from the Komensky terminal on the Pulaski route can be moved. In this case study, the offset can range from 0 to 9 minutes.

- Minimum connection time: this is the walk time needed by transferring passengers between their arrival and departure vehicles. A three-minute value was assumed in this case study for the transfer time between any two connecting lines at any transfer stop.

Based on the operations planning model results from Chapter 4, one can argue that slack time will not be added on Route 53 under the current conditions. The combination of low ratios of transferring passengers to through passengers at the selected transfer stops, high frequency on Route 53, and high variability in vehicle arrival times on all connecting lines makes it uneconomical to add slack at any of the transfer stops along the route. As such, all the recovery time will be maintained at the two termini, Komensky and Peterson. The analysis presented in the next section, therefore, assumes that the operations planning model can only change the terminal departure time of all vehicles on Route 53 with no addition of slack. As in Chapter 4, the expected transfer waiting time becomes the main focus of our discussion.

5.1.3   Results of the Planning Model Application

The operations planning model proposes the departure times for the three selected timepoints on Route 53. The departure times at the remaining timepoints are set based on the new scheduled departure times and the scheduled link travel times between timepoints, which are assumed constant in the model. The scheduled departure times at the termini are also based on the recovery time. The proposed timetable generated by the planning model for the first trip after 10 am is shown in Table 5-7. This timetable recommends dispatching the vehicles on the Pulaski (northbound) line seven minutes later from the Komensky terminal. The timetable for subsequent trips can be easily developed since the headway on Pulaski is constant for the period of analysis. For example, the next trip on the Pulaski (northbound) line will now leave from the Komensky terminal at 10:19 instead of 10:12 am.

Table 5-7. Recommended Service Timetable for Route 53

Northbound Direction

Komensky	Cermak	Roosevelt	Madison	Erie	North	Diversey	Irving Park	Foster	Peterson
10:09	10:15	10:21	10:28	10:34	10:40	10:48	10:58	11:06	11:11

Southbound Direction

Peterson	Foster	Irving Park	Diversey	North	Erie	Madison	Roosevelt	Cermak	Komensky
11:18	11:23	11:29	11:39	11:49	11:55	12:01	12:08	12:14	12:20

To arrive at this schedule, the planning model analyzed all the feasible offset times and selected the value for this decision variable which minimized the total expected transfer waiting time per trip on Route 53 of all impacted passengers at the three timepoints. Figure 5-6 shows this change in expected transfer waiting time per trip for the two different passenger types: T1, the passengers transferring to Route 53, and T2, the passengers transferring from Route 53. The figure shows that the recommended operations plan results in a 15% reduction in total expected transfer waiting time per trip on Route 53.

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Figure 5-6. Expected Transfer Waiting Time per Trip on Route 53 vs. Allowed Offset Times
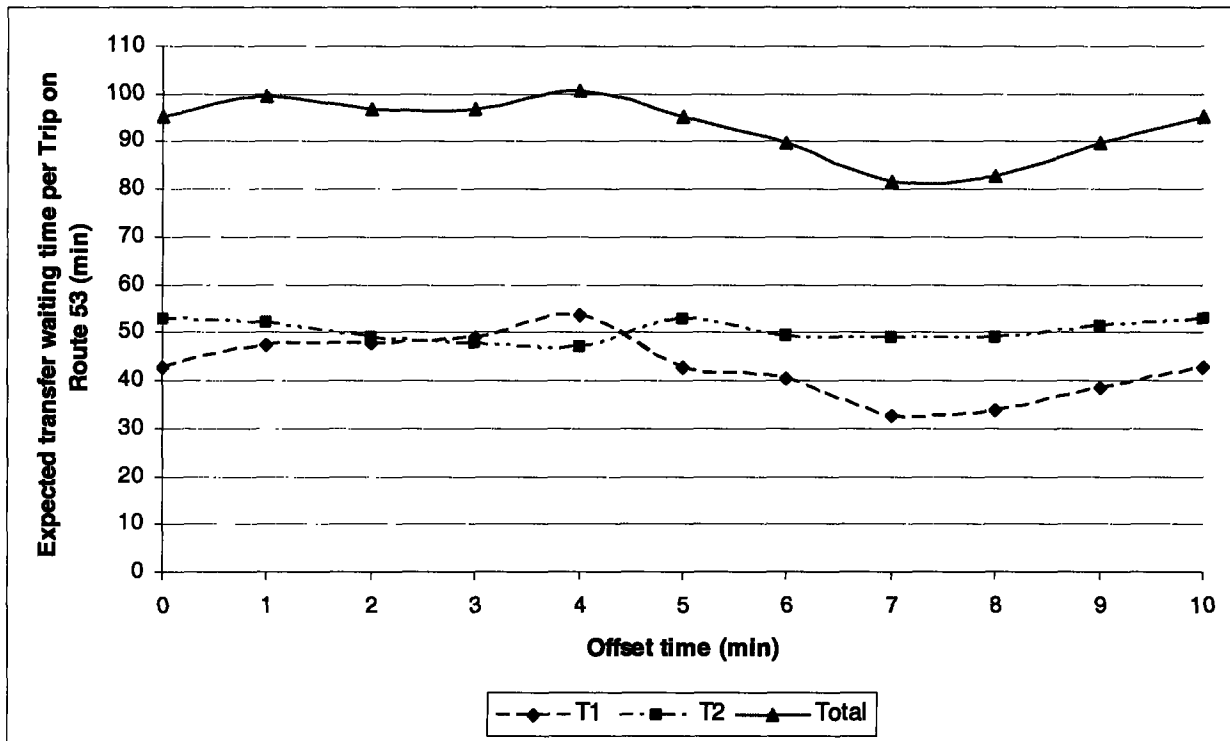
Examining the incidence of passenger benefits, the expected transfer waiting time of T1 passengers is reduced by 23%, from 4.3 to 3.3 minutes/passenger. The expected transfer waiting time of T2 passengers also decreases but by a smaller magnitude (7%), from 5.3 to 4.9 minutes/passenger. This smaller percentage reduction in expected transfer waiting time experienced by T2 passengers is expected given the basic premise of the operations planning model which changes the schedule on Route 53 only and assumes the schedules on the connecting routes remain the same. Greater benefits would be experienced by both T1 and T2 passengers if schedule optimization were extended to all connecting routes. These routes could be scheduled to arrive at the transfer stops at times which allow for shorter connections to and from Route 53. This hypothesis will be tested later in the section.

On average, the expected transfer waiting time decreases from 4.8 to 4.1 minutes/transferring passenger as a result of the new schedule. Not all the transferring passengers, however, experience shorter expected transfer waiting times. Some of them might have to wait longer for their connection as illustrated in Figure 5-7 which shows the expected transfer waiting time per passenger transferring between any two lines at each timepoint: Komensky, North and Irving

Park. A T1(x) passenger transfers to Route 53 from connecting line x, while a T2(y) passenger transfers from Route 53 to connecting line y.

Figure 5-7. Expected Transfer Waiting Time per Transferring Passenger

Pulaski (Northbound)

Pulaski (Southbound)
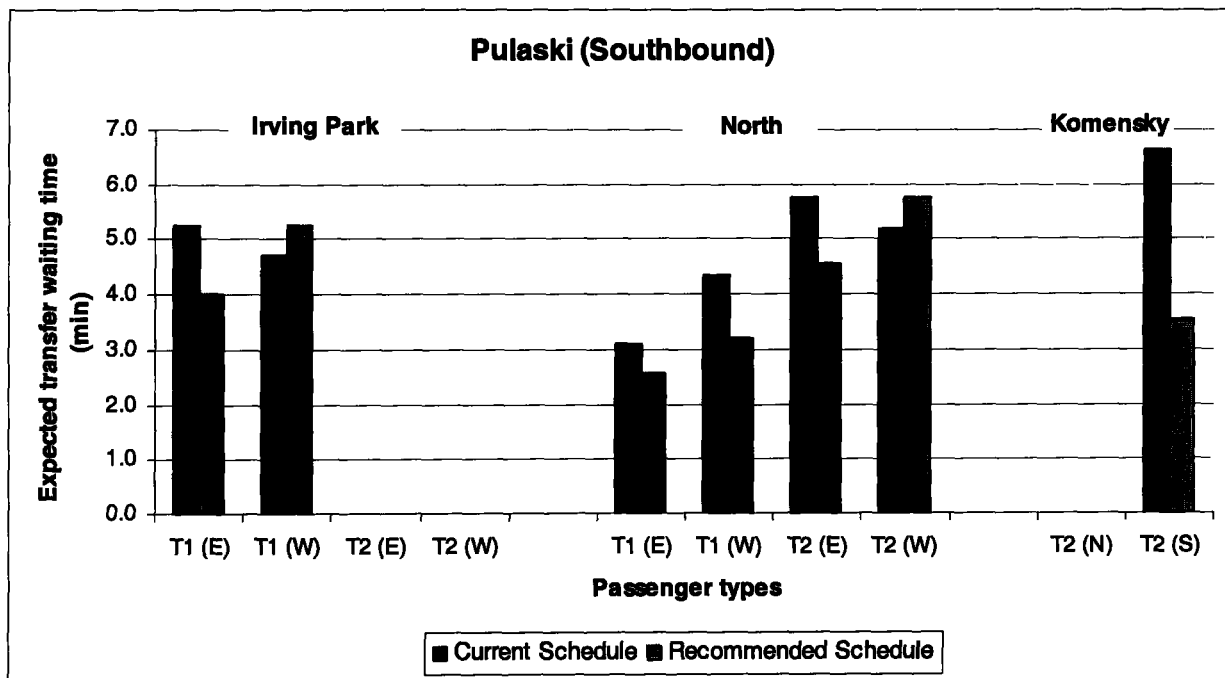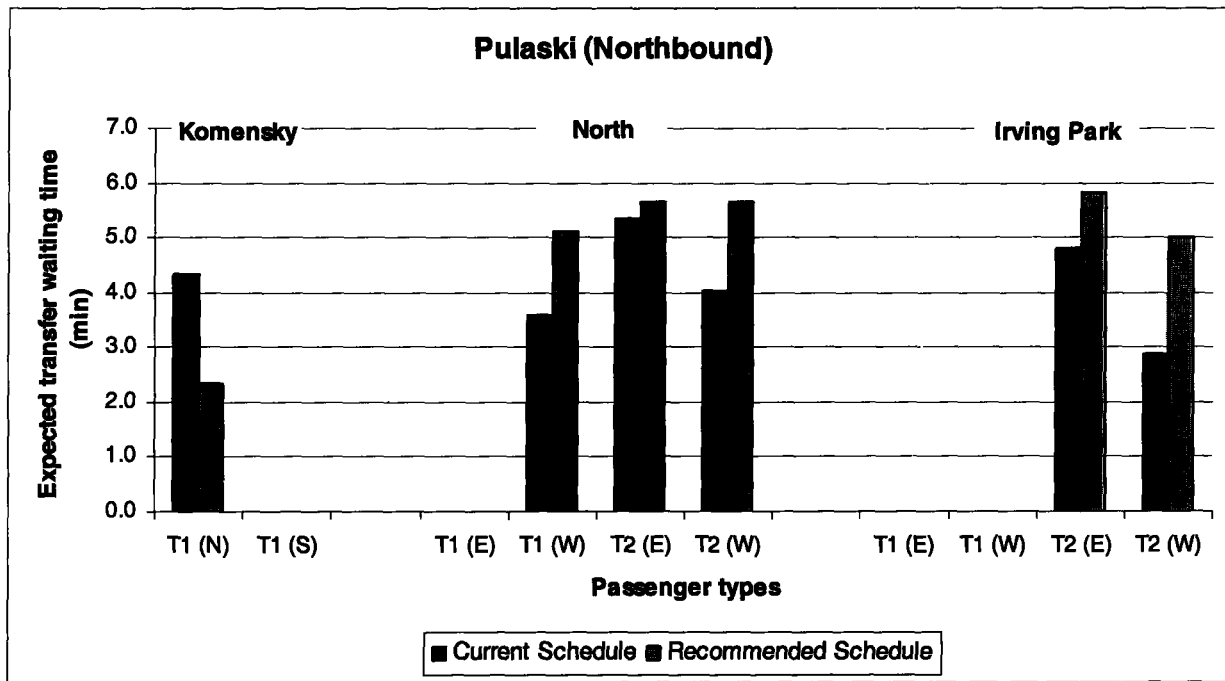
Overall, 50% more passengers benefit from this new timetable than are negatively affected by it (passenger-benefit ratio). On average, the expected time saved per passenger benefiting is about two minutes, whereas each passenger delayed is impacted by less than one minute. Passengers transferring from Pulaski (southbound) to South Pulaski (southbound) at the Komensky terminal experience the greatest time savings due to this new schedule. Their expected transfer wait time is reduced by 47% (from 6.6 to 3.5 minutes/passenger). Those transferring from Pulaski (northbound) to Irving Park (westbound) at the Irving Park timepoint, however, are now delayed by an additional two minutes – a 75% increase in their expected transfer waiting time.

As mentioned earlier, the new timetable that is generated by the operations planning model aims at improving the performance of the selected transfer stops along the corridor. Examining the three transfer stops along Pulaski, the performance of two of these stops – Komensky and North – improves. The greatest benefits are observed at the Komensky terminal where the expected transfer waiting time decreases by about 47%. This reduction in transfer waiting time is experienced by all seven transferring passengers at that terminal. The Irving Park timepoint, on the other hand, experiences deterioration in its transfer performance, with the average expected transfer waiting time increasing by 15% for its transferring passengers (4 passengers/trip).

Further Analysis

Two hypotheses can be made about the application of the operations planning model to Route 53, Pulaski. It is expected that there will be greater expected benefits if:

1. The service reliability of the connecting routes improves, and/or

2. The scheduled departure times on the connecting routes at the transfer stops change

Three additional scenarios (Scenarios 2, 3, and 4) were developed to examine these hypotheses as shown in Table 5-8. Scenario 2 assumes a deterministic distribution for vehicle arrival times on all the connecting routes. Scenarios 3 and 4 are similar to Scenarios 1 and 2 in their vehicle arrival time distributions, however, the schedules on the connecting routes are allowed to change.

Table 5-8. Scenario Specifications

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Arrival Time Distributions	*Pulaksi*	AVL based	Deterministic	AVL based	Deterministic
	Other routes	AVL based	Deterministic	AVL based	Deterministic
Scheduled Departure Times	*North (eastbound)*	Unchanged (10:30:00)		10:33:00	
	Irving Park (eastbound)	Unchanged (10:48:00)		10:51:00	
	Irving Park (westbound)	Unchanged (10:45:00)		10:51:00	

Table 5-9 shows the results of applying the operations planning model under each scenario. These results indicate the sensitivity of the operations planning model to changes in bus arrival time distributions as well as to changes in the model structure itself.

Table 5-9. Model Results for the Different Scenarios

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Departure Offset		7	6	7	6
Total Exp. WT / Trip	*Current*	95.4	115	97.4	130
	Recommended	81.5	70	78.0	35
Exp. WT / Transferring Passenger	*Current*	4.8	5.8	4.9	6.5
	Recommended	4.1	3.5	3.9	1.8
% Saving in Exp. WT of T1 Passengers		23.5%	66.0%	21.2%	70.0%
% Saving in Exp. WT of T2 Passengers		7.4%	16.1%	19.1%	75.0%
% Saving in Total Exp. WT		14.6%	39.1%	20.0%	73.1%
Passenger-Benefit Ratio		1.5	2.3	2.8	19

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Comparing the results from the model application to Scenarios 1 and 2 and Scenarios 3 and 4 strongly supports the first hypothesis: the expected benefits from operations planning increase as the variability in vehicle arrival times decreases. The percentage savings in total expected transfer waiting time increase from 14.6% (Scenario 1) to 39.1% (Scenario 2) and from 20.0% (Scenario 3) to 73.1% (Scenario 4). This translates to savings in passenger-minutes per day for the period of analysis from 167 (Scenario 1) to 540 (Scenario 2) and from 233 (Scenario 3) to 1140 (Scenario 4). The ratio of passengers benefiting from the new schedule to those being delayed by it, as indicated by the passenger-benefit ratio, also increases with the decrease in arrival time variability showing that more transferring passengers are now benefiting from the recommended schedule.

Looking at Scenario 2, one notes that the percentage time savings experienced by both T1 and T2 passengers increase from Scenario 1. However, the reduction in expected transfer waiting time of T1 passengers is still higher than that of T2 passengers. This is due to the structure of the operations planning model which changes the schedule on Route 53 only and assumes the schedules on the connecting routes to remain the same. In fact, allowing the schedules of these connecting routes to change results in greater expected benefits to all impacted passengers. This hypothesis is verified by comparing Scenarios 1 and 3. For the same stochastic vehicle arrival time distribution, the planning model results in a greater reduction in total expected transfer waiting time if the vehicle arrival times on some of the connecting routes are allowed to change. This percentage time saving is now shared almost equally by both T1 and T2 passengers in Scenario 3. Although the percentage reduction in expected transfer waiting time of T1 passengers remains approximately the same as in Scenario 1, that of T2 passengers increases by a factor greater than two. This is expected since the connecting vehicles are now scheduled to arrive at the transfer stops so as to allow good connections with Route 53.

The benefits from adopting a network approach to schedule optimization become more pronounced as the variability in vehicle arrival times decreases. This is evident by examining and comparing Scenarios 2 and 4. When the scheduled departure times on North (eastbound) and Irving Park (eastbound and westbound) are allowed to change (Scenario 4), the percentage reduction in total expected transfer waiting time per trip is 73% (compared to 39% in Scenario 2) as a result of the recommended service timetable. Under this schedule, nineteen (out of a total of twenty) transferring passengers save time of five minutes per passenger. The three timepoints selected for analysis experience improvements in their transfer performance with the greatest benefits observed at the Komensky terminal. Under Scenario 4, the percentage time

savings experienced by T2 passengers are greater than those experienced by T1 passengers as expected. In fact, with an appropriate selection of arrival times on the connecting lines at the transfer stops, the expected transfer waiting time of T2 passengers can be reduced to zero. Under Scenario 4, T2 passengers now save time amounting to six minutes per passenger compared to three and a half minutes saved by T1 passengers. Under Scenario 2, the opposite is true where T1 passengers still save three and a half minutes per passenger (the same offset time is recommended for both Scenarios 2 and 4) while T2 passengers save only one minute.

5.1.4   Application of the Control Model

A vehicle arriving at a transfer stop on Pulaski is considered for holding if such a decision will allow passengers – who are arriving on a connecting vehicle and who wish to transfer to the held vehicle – to make their connection successfully. As such, the major group of passengers benefiting from real-time transfer coordination is obviously these transferring passengers who will now enjoy shorter transfer waiting times. However, at the same time, a holding decision delays and inconveniences other passengers, particularly those onboard the vehicle being held and those already waiting at downstream locations. This being said, for any holding decision to produce net benefits, there need to be a large number of passengers who wish to transfer to the held vehicle.

During the period 10 am to noon, the number of passengers transferring to Pulaski is divided evenly among all transfer stops, with the directional transfer movements at each stop being one, or less, passengers per trip. The only three stops where the number of passengers per trip transferring to Pulaski from a connecting line is greater than one are at the Komensky terminal and at the Cermak and Roosevelt timepoints. At Komensky, four passengers per trip transfer from South Pulaski (northbound) to Pulaski (northbound). At Cermak, two passengers per trip transfer from Cermak (eastbound) to Pulaski (northbound), and at Roosevelt, three passengers per trip transfer from Roosevelt (westbound) to Pulaski (northbound).

At both Cermak and Roosevelt, the combination of the low ratio of the number of transferring passengers to Pulaksi to the number of through passengers (0.3 and 0.2 respectively) and the frequent service on Pulaski suggest that vehicle holding is not appropriate at any of these transfer stops. The additional delay incurred by negatively affected passengers will outweigh the time savings experienced by benefiting passengers most of the time. One can argue that holding might be appropriate at Komensky since there are no through passengers at the

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terminal. Figure 4-11 showed that the probability of holding a "ready" vehicle is approximately 100% at stops where the ratio of transferring to through passengers is very high. However, the effects of holding a vehicle at the stop analyzed in Chapter 4 were limited to that stop and only one downstream stop. Holding a vehicle at the Komensky terminal will influence the transfer performance at all downstream transfer and non-transfer stops. As such, the probability of holding a vehicle on Pulaski at Komensky for an incoming vehicle on South Pulaksi will not be as high. Moreover, holding should only be considered if the connecting vehicle has already arrived at the terminal and the transferring passengers have started the transfer process.

5.2 ROUTE 63

This section presents the current conditions on route 63 and the results of the application of the operations planning model to improve transfer performance on that route. Sensitivity analysis results are also presented and discussed.

5.2.1   Route Characteristics

Route 63 runs east-west on the south side of Chicago with terminals at Midway and Stony Island. There are nine timepoints on the route including the two termini as shown in Figure 5-8. The time period selected for analysis was Saturdays between noon and 3 pm. The characteristics which make Route 63 a promising candidate for transfer coordination in this time period are:

- Route 63 connects with eighteen bus routes and four rail lines and has an average total of 3088 transferring passengers on Saturdays between noon and 3 pm. This ranks Route 63 fourth among all CTA bus routes in terms of total transfer activity, with the first route – Route 9 – having approximately 40% more transfers.

- Currently, the mean expected transfer waiting time per passenger was estimated to be 4.6 minutes at the selected transfer stops to be analyzed with the operations planning model.

- Between noon and 3 pm, the headways of four bus routes and one rail line are compatible with the six minute headway on Route 63.

Similarly to Route 53, the ratio of transferring passengers to through passengers at each transfer stop along the corridor is very low. The number of transferring passengers on Route 63 is divided almost equally among all transfer stops, with the directional transfer movements at each stop being one or zero passengers per trip in most cases.

Figure 5-8. CTA Route 63, 63rd Street
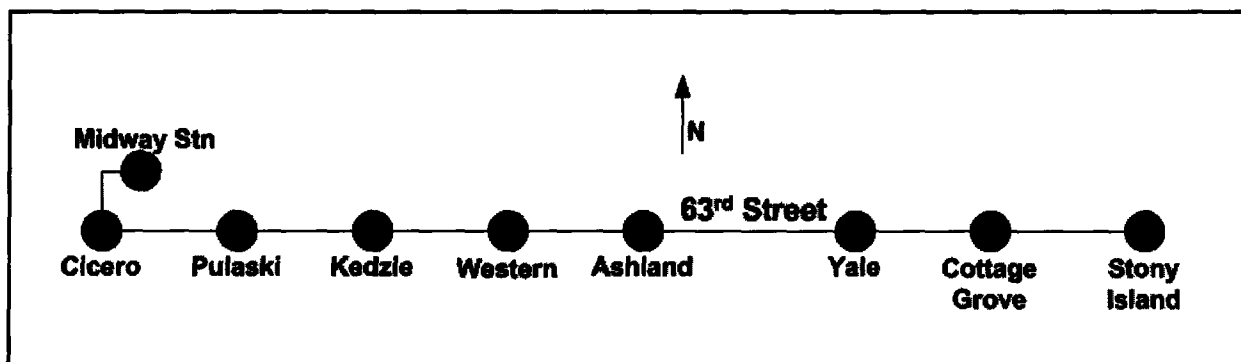
The service timetable at the nine timepoints along Route 63 in both directions is summarized in Table 5-10 for the first trip after noon with a following headway of six minutes.

Table 5-10. Current Service Timetable for Route 63

Eastbound Direction

Midway	Cicero	Pulaski	Kedzie	Western	Ashland	Yale	Cottage Grove	Stony Island
12:13:30	12:17:30	12:22:30	12:27:30	12:32:30	12:37:30	12:52:00	13:00:00	13:08:00

Westbound Direction

Stony Island	Cottage Grove	Yale	Ashland	Western	Kedzie	Pulaski	Cicero	Midway
13:16:00	13:24:00	13:32:00	13:46:30	13:51:30	13:56:30	14:01:30	14:06:00	14:10:00

The eastbound half-cycle time on Route 63 is sixty-two and a half minutes including eight minutes of recovery time currently built-in at the Stony Island terminal, and the westbound half-cycle time is sixty-three and a half minutes including nine and a half minutes of recovery time

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built-in at Midway. The recovery times are 13% and 15% of the scheduled running times eastbound and westbound, respectively.

5.2.2   Application of the Planning Model

As discussed in Chapter 3, the transfer stops that are included in the application of the operations planning model must be timepoints and must have connecting lines with headways compatible with Route 63. The bus and rail routes which connect with Route 63 at its timepoints and which have scheduled headways constant over this three-hour period and compatible with six minutes are shown in Table 5-11. Route 63W (West 63rd) connects with Route 63 at Midway, the Red Line connects at Yale, and Routes 6 (Jackson Park Express) and 28 (Stony Island Express) connect at Stony Island terminal as shown in Figure 5-9. As such, three timepoints – out of nine – will be included in this application of the operations planning model.

Table 5-11. Intersecting Route Headways

Rt. 63W	Red Line	Rt. 6	Rt. 28
30 min	6 min	12 min	12 min

Figure 5-9. Application of the Planning Model
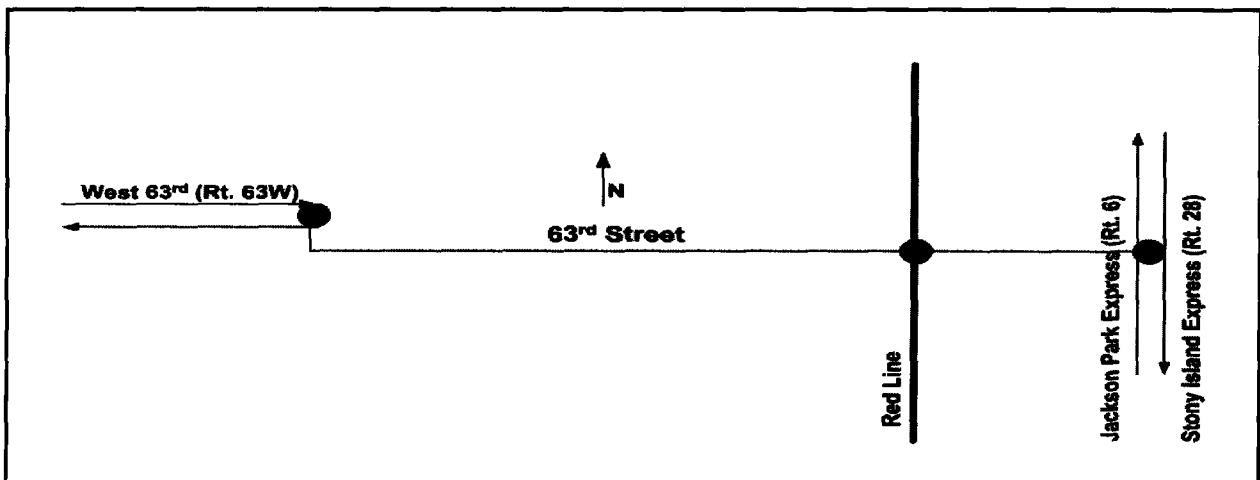
Model Inputs

The inputs to the operations planning model can be grouped into three distinct categories:

- Arrival time distributions of the lines connecting at the three selected transfer stops: the data used to obtain these empirical distributions came from six Saturdays in March and April 2004. A summary of these distributions is shown in Table 5-12.

Table 5-12.Summary of Arrival Time Distributions of Connecting Routes at the Selected Stops

Midway Terminal

Route #	Direction	Scheduled Departure Time	Mean Deviation from Schedule	Standard Deviation	Minimum Deviation from Schedule	Maximum Deviation from Schedule
63	Eastbound	12:13:30	_	_	_	_
	Westbound	14:10:00	0.41 min	2 min	-2 min	4 min
63W	Eastbound	12:28:30	3.74 min	1.48 min	1 min	6 min
	Westbound	12:10:00	_	_	_	_

Yale Timepoint

Route #	Direction	Scheduled Departure Time	Mean Deviation from Schedule	Standard Deviation	Minimum Deviation from Schedule	Maximum Deviation from Schedule
63	Eastbound	12:52:00	-1 min	2.45 min	-5 min	3 min
	Westbound	13:32:00	2.3 min	2.1 min	-1 min	6 min
Red Line	Northbound	12:53:00	-0.25 min	2.9 min	-4 min	4 min
	Southbound	12:53:00	-0.7 min	2.75 min	-5 min	3 min

Stony Island Terminal

Route #	Direction	Scheduled Departure Time	Mean Deviation from Schedule	Standard Deviation	Minimum Deviation from Schedule	Maximum Deviation from Schedule
63	Eastbound	13:08:00	-0.29 min	2.09 min	-4 min	4 min
	Westbound	13:16:00	_	_	_	_
6	Northbound	13:09:30	-0.16 min	3.1 min	-5 min	4 min
	Southbound	13:15:00	-0.4 min	2.38 min	-4 min	4 min
28	Northbound	13:01:30	-0.34 min	3.0 min	-5 min	4 min
	Southbound	13:02:00	-2.1 min	4.65 min	-5 min	1 min

■ Through passenger and transfer passenger volumes on the intersecting lines: through passenger volumes were obtained from the APC system. The average numbers of through passengers at the Yale timepoint are 12 and 20 passengers per eastbound and westbound trip respectively. Transferring passenger volumes were estimated according to the process described earlier for Route 53. Table 5-13 summarizes the transfer movements between all the connecting lines.

■ User-related parameters: these are summarized in Table 5-14.

Table 5-13. Directional Transfer Movements between All Connecting Routes (Pax/trip)

From \ To	63W (E)	63W (W)	Red Line (N)	Red Line (S)	6 (N)	6 (S)	28 (N)	28 (S)
63 (E)	–	–	1	1	1	–	1	–
63 (W)	–	1	–	–	–	–	–	–

To \ From	63W (E)	63W (W)	Red Line (N)	Red Line (S)	6 (N)	6 (S)	28 (N)	28 (S)
63 (E)	1	–	–	1	–	–	–	–
63 (W)	–	–	–	–	–	1	–	–

Table 5-14. User Related Inputs

Departure Offset Time	Offset time ranges from 0 to +5 minutes
Minimum Connection Time	Time to transfer between any two connecting lines at any stop is 3 minutes

The total transfer activity on Route 63 is only 8 passengers/trip out of a total of 103 passengers/trip if all transfer stops on the corridor are considered. Again, the combination of low ratios of transferring passengers to through passengers at the selected transfer stops, high frequency on Route 63, and high variability in vehicle arrival times on all connecting lines makes it uneconomical to add slack at any of the transfer stops along the route. The analysis presented in the next section, therefore, assumes that the operations planning model only changes the terminal departure time of vehicles on Route 63 with no addition of slack.

5.2.3 Results of the Planning Model Application

The new timetable proposed by the planning model for the first trip in the period under analysis is shown in Table 5-15. This timetable recommends dispatching the vehicles on Route 63 (eastbound) three minutes later from the Midway terminal. The timetable for subsequent trips

can be easily developed since the headway on Route 63 is constant for the period of analysis. For example, the next trip will now leave from Midway at 12:22:30 instead of 12:19:30.

Table 5-15. Recommended Service Timetable for Route 63

Eastbound Direction

Midway	Cicero	Pulaski	Kedzie	Western	Ashland	Yale	Cottage Grove	Stony Island
12:16:30	12:20:30	12:25:30	12:30:30	12:35:30	12:40:30	**12:55:00**	13:03:00	**13:11:00**

Westbound Direction

Stony Island	Cottage Grove	Yale	Ashland	Western	Kedzie	Pulaski	Cicero	Midway
13:19:00	13:27:00	**13:35:00**	13:49:30	13:54:30	13:59:30	14:04:30	14:09:00	**14:13:00**

To arrive at this schedule, the planning model analyzed all the feasible offset times and selected the value for this decision variable which minimized the total expected transfer waiting time per trip on Route 63 of all impacted passengers at the three timepoints. The figure shows that the recommended operation results in less than a 1% reduction in total expected transfer waiting time per trip on Route 63. This agrees with the findings from Chapter 4 where it was shown that it is not worth coordinating schedules when the headway on the main corridor is short and the arrival time variability is high. Because vehicles run frequently on Route 63, the expected waiting time of T1 passengers is very short even in the current timetable (2.5 minutes/passenger). On the other hand, the expected waiting time of T2 passengers is long but cannot be reduced since many of these passengers still have to wait for the vehicles on their twelve (Routes 6 and 28) and thirty (Route 63W) minute headway destination lines (compared to the six minute headway on their arriving line).

Figure 5-10 shows the change in expected transfer waiting time per trip for the two different passenger types: T1, the passengers transferring to Route 63, and T2, the passengers transferring from Route 63. The figure shows that the recommended operation results in less than a 1% reduction in total expected transfer waiting time per trip on Route 63. This agrees with the findings from Chapter 4 where it was shown that it is not worth coordinating schedules

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when the headway on the main corridor is short and the arrival time variability is high. Because vehicles run frequently on Route 63, the expected waiting time of T1 passengers is very short even in the current timetable (2.5 minutes/passenger).On the other hand, the expected waiting time of T2 passengers is long but can not be reduced since many of these passengers still have to wait for the vehicles on their twelve (Routes 6 and 28) and thirty (Route 63W) minute headway destination lines (compared to the six minute headway on their arriving line).

Figure 5-10. Expected Transfer Waiting Time per Passenger vs. Allowed Offset Times
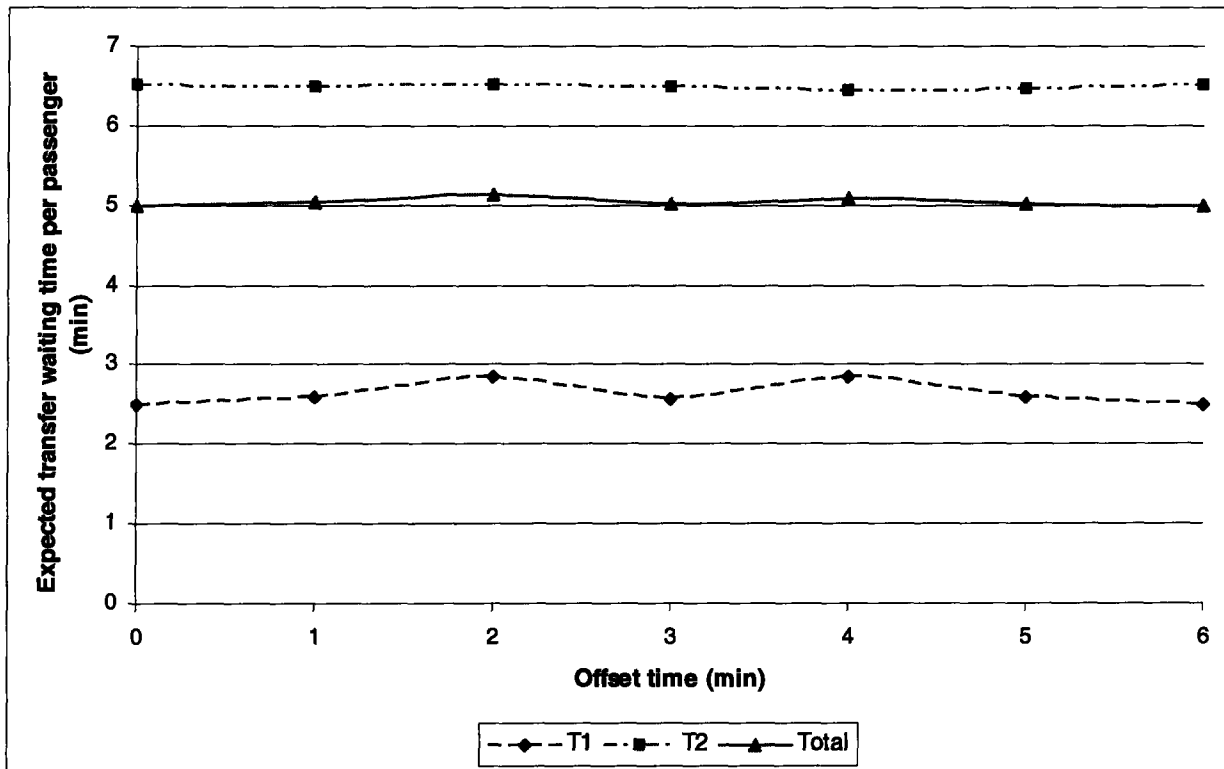
5.2.4   Application of the Control Model

During the period noon to 3 pm, the number of passengers transferring to route 63 is divided among all the transfer stops, with the directional transfer movements at each stop being one, or less, passengers per trip. Since the numbers of transferring passengers at any stop are very low compared to the number of through passengers and since the headway on Route 63 is very short, holding is not appropriate during the period under analysis.

6 CONCLUSION

This is the concluding chapter of the thesis. Section 6.1 briefly describes the operations planning and operations control models that were developed to analyze transfer coordination on a transit corridor. The major findings from the application of each model to a hypothetical route are summarized in Section 6.2. Recommendations to CTA as a result of applying the models to two specific bus corridors are presented in Section 6.3. Finally, Section 6.4 suggests model extensions and new topics for future research

6.1 SUMMARY

The continuing shift of activities from city centers to other parts of the metropolitan area is resulting in increasingly dispersed origin-destination patterns. Providing direct public transportation service for these dispersed demand patterns is very expensive if not infeasible for any agency regardless of its size and available resources. That is why most agencies rely on the willingness of their passengers to transfer between routes or services to complete their trips. However, transfers usually reduce the attractiveness of transit because they add uncertainty, discomfort, waiting time and cost to most trips. Transfer coordination initiatives can reduce the disutility of transfers in transit networks by minimizing the expected waiting times of transferring passengers. Transit agencies believe that effective coordination will significantly increase the attractiveness and productivity of their intermodal and/or intramodal transit systems by improving service quality and attracting new ridership. This research focused on understanding the different strategies that minimize transfer waiting time – which is the primary driver of customer satisfaction – and on developing models that can be used to improve connectivity on a transit corridor with multiple transfer stops. The remaining objectives of the research included applying the models to a hypothetical route to determine which operating conditions result in the greatest benefits as well as applying them to two CTA bus corridors: Routes 53 and 63.

The first goal of this research involved a review of the existing literature related to transfer coordination schemes. In general, transfer waiting time can be reduced through the implementation of schedule coordination and/or real-time coordination strategies – also referred to as operations planning and/or operations control strategies. Schedule coordination involves

modifying the current service timetable of connecting routes in order to minimize the overall passenger transfer waiting time in the network and to improve its transfer performance. Three strategies were discussed: changing the departure time from the terminals of the vehicles on the connecting routes, adding slack time to the schedule of the routes at different transfer stops, and adjusting the service frequencies. Real-time coordination systems, on the other hand, utilize the current network information (vehicle arrival times and passenger demand based on ITS technologies) to select dispatch times which optimize the transfer performance in real-time. The most widely used strategy is holding a vehicle which is ready to be dispatched from a transfer stop to allow arriving transferring passengers to complete their connection. The conditions under which each operations planning and operations control strategy has proven most effective were reviewed and the impacts of each strategy were presented.

Two computer models – one for operations planning and the other for operations control– were then developed to assess scheduling and real-time holding decision rules for vehicles on a transit corridor in order to improve its transfer performance. The operations planning model involves the simultaneous application of two planning strategies: changing the terminal departure time and inserting slack time, and aims at coordinating transfers at selected transfer stops along the corridor so as to improve the overall experience for passengers. The model analyzes all the feasible offset/slack time combinations and recommends a new service timetable for the analysis corridor which minimizes the total expected (weighted) waiting time of all impacted passengers along that corridor. The operations control model is developed and applied separately from the planning model. The aim is to determine under what conditions holding a vehicle at a transfer stop for an incoming connecting vehicle is an appropriate strategy. The model is designed to utilize the current operating conditions of the network, to consider the impacts of any decision on the different passenger categories at, and downstream of, the transfer stop in question, and to finally recommend either holding or dispatching the "ready" vehicle based on the overall net benefits measured in passenger-minutes saved.

The two models were tested on a hypothetical corridor to illustrate their applicability in coordinating transfers. The sensitivity of the decision variables and the model results to exogenous factors including headways, bus arrival time variance, transfer volumes and passenger time values were also explored. Finally, the models were applied to two bus corridors at CTA: Routes 53 and 63. The major findings from the application to the hypothetical case and the recommendations from the CTA case studies are presented in the following two sections.

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6.2 MAJOR FINDINGS

This section summarizes the major findings from the application of the operations planning and operations control models to a hypothetical corridor and the results of the different sensitivity analyses that were conducted on that corridor.

6.2.1 Operations Planning Model Results

The results from the application of the operations planning model to the hypothetical route proved to be quite robust as the service timetable recommended by the model remained unchanged for the different sensitivity analyses. This timetable involved changing only the departure time from the terminal of all vehicles on the corridor with no addition of slack time to the schedule at the different timepoints. This is expected since slack is not usually introduced into the schedule when the service headway on the analysis route is short, the ratio of the number of transferring passengers to the number of through passengers at the transfer stops is low, and/or the standard deviations of vehicle arrival times at the transfer stops are high (these represent the baseline operating conditions on the hypothetical route).

Sensitivity analyses showed that there are very few benefits from coordinating transfers when the headway on the analysis corridor is short because short headways usually imply short expected transfer waiting times. However, as the headway on the analysis corridor increases, the benefits from transfer coordination increase substantially (see Figure 4-3). A similar trend is observed when the variance of vehicle arrival times is altered. The benefits accruing from better scheduling increase as the variability in vehicle arrival times decreases (see Figure 4-4). In fact, the percentage reduction in the total expected transfer waiting time increased to 48% when vehicle arrival times were assumed deterministic in the system. Operations planning benefits are thus the greatest when there is little variability in vehicle arrival times. No change in the total expected transfer waiting time was observed, however, when the transfer demand to the analysis corridor was increased or the time ratio was altered because the same schedule was still recommended by the model.

A basic premise behind the operations planning model is that it only changes the schedule on the selected corridor while assuming that the schedules on its connecting routes stay the same. As such, it was expected that the recommended timetable would limit the actual benefits that can be obtained from better scheduling on the analysis corridor. Allowing the schedules of the

connecting routes also to change verified the hypothesis since it resulted in greater expected benefits to all impacted passengers for the same vehicle arrival time distributions. The benefits from adopting a network approach to schedule synchronization became even more pronounced as the variability in vehicle arrival times decreased.

6.2.2   Operations Control Model Results

The operations control model was applied to the last transfer stop on the analysis corridor, with the impacts of any holding/dispatching decision studied both at that stop as well as at the one remaining downstream stop. The numerical results presented in Chapter 4 and summarized below should therefore be evaluated within this context and should not be generalized to all transfer stops.

It was shown that the probability of holding a vehicle, which was ready to be dispatched from a transfer stop, for an incoming connecting vehicle decreases as the minimum holding benefit threshold set by the transit agency increases (see Figure 4-6). It was also shown that, for a particular minimum holding benefit threshold, the conditional probability of holding a "ready" vehicle decreases as the required holding time increases (see Figure 4-7). This conditional probability also decreases if the preceding headway of the vehicle is long and its following headway is short (see Figure 4-8). This is expected since the vehicle to be held will have more through passengers and more boarders who will be negatively impacted by a hold. On the other hand, the missed connection cost of transferring passengers – who are the main beneficiaries of a hold – will be small given the short following headway. As such the greatest benefits occur when the required holding time and the preceding headway of the vehicle on the destination line are short and its following headway is long.

At low transfer demand to the analysis corridor at the transfer stop under study, the probability of holding a "ready" vehicle increased only modestly with increase in the scheduled headway (see Figure 4-9) and/or with increase in the time ratio (see Figure 4-13). However, as the transfer demand increased, the probability increased significantly reaching approximately 100% when the number of transferring passengers was 30% more than the number of through passengers at that stop (see Figure 4-11). The application of the control model to the transfer stop under study showed that transfer demand is a major driving factor behind any holding recommendation because it affects the missed connection cost which, at high transfer volumes, becomes the major part of the total cost.

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As discussed earlier, the operations control model was tested and applied separately from the planning model in this research. However, the impact of adopting a sequential approach to transfer coordination which involved optimizing offset and slack times beforehand was also investigated. Results showed that the "ready" vehicle was dispatched immediately 91.8% of the time since its expected departure time from the transfer stop – under the new service timetable – now allowed transferring passengers to complete their connection. For the hypothetical corridor, it was shown that as the variance of the vehicle arrival times decreases, a "ready" vehicle will never be held at the transfer stop under study since the recommended operations plan will have already optimized the transfer performance along the corridor.

6.3 CTA RECOMMENDATIONS

The results of the specific CTA case studies are reviewed and both general recommendations to CTA and specific recommendations regarding these routes are provided in this section.

6.3.1 Route 53

The operations planning model was applied to Route 53 for weekdays during the period 10 am to noon. During this time period, the route ranks six among the heaviest CTA routes in terms of total transfer activity. Only three out of the ten timepoints along that route were eligible for analysis because only they had connecting routes with headways compatible with the ten-minute headway on Route 53. This compatibility requirement meant that only 20 out of 129 passengers/trip are amenable to schedule coordination improvements.

The new timetable recommends dispatching all vehicles seven minutes later from the Komensky terminal without adding any slack to the schedule en route. This is expected due to the combination of low ratios of transferring passengers to through passengers at the selected transfer stops, high frequency on the route, and high variability in vehicle arrival times on all connecting routes.

The recommended operations plan results in a 15% reduction in the total expected transfer waiting time (see Figure 5-6) which translates to savings of 167 passenger-minutes per day for the period of analysis or an average reduction of less than a minute per transferring passenger. Overall, 50% more passengers benefit from the proposed timetable than are negatively affected by it (passenger-benefit ratio). On average, the expected time saved per passenger benefiting is

about two minutes, whereas each passenger negatively affected is impacted by less than one minute. Although the benefits accrued from coordinating schedules on this route are not great, it is still worthwhile to change the route's service timetable since there is no resulting change in operating cost.

On the other hand, it is uneconomical to invest in real-time coordination initiatives along Route 53. The low ratios of the number of transferring passengers to the number of through passengers at almost all transfer stops and the frequent service on the route suggest that holding a "ready" vehicle will most likely never be justified at any transfer stop. The additional delay incurred by negatively affected passengers will outweigh the time savings experienced by benefiting passengers. Holding a vehicle on Pulaski might be appropriate only at the Komensky terminal if the connecting vehicle from South Pulaski has already arrived and the transferring passengers have started the transfer process. As such, it might be worthwhile positioning a supervisor at the Komensky terminal who can communicate with the bus operator of the vehicle on Route 53A to estimate the arrival time of that vehicle and approximate the number of transferring passengers. Having this information, the supervisor can then rely on his judgment and experience to make informed real-time decisions.

6.3.2   Route 63

Route 63 ranks fourth among the heaviest CTA routes in terms of total transfer activity on Saturdays between noon and 3 pm. Similarly to Route 53, the headway compatibility requirement lead to a very small fraction of the transfers (less than 8%) to be amenable to improvement.

The operations planning model recommends dispatching all vehicles on Route 63 three minutes later from the Midway terminal during the time period under study. However, the new timetable results in less than 1% reduction in total expected transfer waiting time for all impacted passengers (see Figure 5-10). This is due to the combination of the short six-minute headway on Route 63 and the high variability in vehicle arrival times on all connecting routes at the three transfer stops that were analyzed. As such, it is not worth to coordinate schedules on this route.

The combination of the short headway and the low ratios of the number of transferring passengers to the number of through passengers at all transfer stops along Route 63 also suggest that real-time coordination is not appropriate during the period of analysis.

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6.3.3   General Recommendations

Chicago is a dispersed city with origins and destinations spread widely over a large area. Both bus and rail are utilized extensively throughout the network and so there is a huge dependency on good connectivity to be effective. Despite this, connectivity has not been a primary focus of planning or scheduling in recent years at CTA. This has affected a large number of passengers who have to transfer to routes with no schedule coordination and hence suffer long transfer waiting times. One exception is the night owl service in which the departure times of several routes are coordinated from a downtown intersection hence minimizing the expected waiting times of transferring passengers.

The night owl service is the only instance where the needs of transferring passengers are accounted for explicitly. In general the schedules of the CTA routes are not coordinated with the intention of reducing the transfer waiting time. As Crockett [2002] suggested, the CTA service standards should recognize the importance of good connectivity within the network and should therefore impose certain requirements concerning the maximum allowable transfer waiting time that can be introduced in the schedule of connecting routes.

The waiting time savings accrued from coordinating schedules on Route 53 were not very significant for a number of reasons, one relating to the small number of transfer stops that were analyzed in the planning model due to the incompatibility of headways on the remaining stops. Another recommendation made by Crockett [2002] and which applies directly to this research is that CTA standardize its headways and require that all headways be 10, 20, or 30 minutes in the off peak period. This would make schedule coordination easier to implement on many high transfer routes and should result in greater overall system benefits.

Connections to high frequency routes at CTA are not a problem since the transfer waiting times should never be excessive. Connections to low frequency routes also do not immediately lead to long transfer waiting times. The main factor which influences the transfer waiting time is service reliability on the different connecting routes. Results showed that it is not worth applying schedule coordination on routes with high variability in vehicle arrival times because the expected benefits are negligible. Having examined a number of CTA routes, it seems that service reliability should be improved significantly in the network before the maximum benefits of schedule coordination can be attained.

The transfer stops analyzed for real-time coordination in this research showed that it is not worth investing in this form of transfer coordination mainly because the transfer demands to the analysis corridors were very low at these stops. This finding can not be generalized to the whole CTA network, however, because there are many transfer stops within that network with very high transfer volumes especially between connecting rail lines. As such, more research should be done in this field before deciding to pursue further investment in real-time tracking technology. For the time being, supervisors and/or bus operators should rely on communication to make informed holding decisions. The practice currently adopted at CTA is to hold a "ready" vehicle at a transfer stop if the connecting vehicle has already arrived and this is likely to be an effective as well as easy-to-implement control policy.

6.4 FUTURE RESEARCH

Possible extensions of the operations planning and operations control models developed in this research are suggested in this section. Some additional aspects of transfer coordination are also discussed.

6.4.1 Operations Planning Model Extensions

The operations planning model can be extended in various ways:

- The model assumes passenger demand to be inelastic and therefore does not predict changes in demand as a result of new route schedules. One extension would be integrating the planning model with an elasticity based demand model to optimize schedule coordination iteratively. It would be interesting to see whether the benefits from better scheduling are sufficient to attract a larger ridership base and to increase revenue for the transit agency.

- The model assumes that the recommended offset at the two route terminals is the same since the scheduled half-cycle times in each direction remain unchanged. Relaxing this assumption and allowing the model to change the half-cycle times in each direction while maintaining the same scheduled cycle-time might enhance the model capabilities.

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- The model can be revised to make it easier to use. The pre-processing portion of the operations planning model which involves preparing the input files from AVL, APC and AFC data and the post-processing portion of the model which involves some additional calculation if the headways on some of the connecting routes are integer multiples can be built into the model saving the user time and making the model easier to use by transit agencies.

6.4.2   Operations Control Model Extensions

The operations control model can also be extended in various ways:

- Similarly to the planning model, an elastic demand model can be integrated with the operations control model to observe and analyze the results of the application of real-time coordination upon ridership within the system over the long haul.

- The operations control model assumes that if a "ready" vehicle is held at a transfer stop, then all the connecting passengers will be able to board it with no capacity concerns. This may not always be true and some transferring passengers might be forced to wait for the next arriving vehicle. It would be interesting to examine the results of the application of the operations control model when these left-over passengers are properly accounted for.

6.4.3   Coordination Approach

The approach adopted in this research for coordinating transfers involves the separate and independent application of the operations planning and the operations control models. A different approach that might yield greater overall benefits is the simultaneous application of both models whereby control guidelines affect and feed into the recommended operations plan. It is expected that – for such an approach – there will be a high threshold for adding slack time to the schedule of any route. Slack time will be introduced at a transfer stop only if there is a high transfer demand at that stop which is repetitive for every trip during the period under study.

In this research, schedule coordination was applied at the route level. A new service timetable was recommended by the model for the analysis corridor while the schedules on all the connecting routes were assumed unchanged. Results of the sensitivity analyses showed that it may be more valuable to coordinate transfers at the network level since greater benefits are expected. If a network-approach is adopted, the complexity of the planning model is expected to

increase significantly because the schedules on all the routes now need to be optimized simultaneously. However, it is likely that a successful implementation of a network-wide schedule coordination system would produce significant passenger benefits and would have important applications to transit operations on the whole. It would be interesting and valuable to apply such a network-wide approach to the operations control model as well.

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