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Canada

Study of Dynamic Headway Control Bus Dispatching Rules

By

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A Thesis Presented to the University of Ottawa
in Fulfilment of the Thesis Required for
the Degree of Master of Science
(Systems Science)

UNIVERSITÉ D'OTTAWA
UNIVERSITY OF OTTAWA

ACKNOWLEDGEMENTS

I am extremely grateful to Dr. François M. Julien, who has supervised me in my thesis work for the past twelve months, for his generous support, inspiring ideas in the research and his great effort and patience in guiding me to prepare this thesis.

I wish to express my gratitude to professor Jeffrey Sidney, my co-supervisor, professor Dan Lane and professor John Nash for their support, encouragement and academic suggestions.

A special word of thanks goes to professor Klaus Kannemann, whose constructive ideas have helped me to solve the problems I had in my programming of the user interface.

Profound thanks also go to Dr. Helen Gault and Mr. Joel Koffman from the Systems Planning Department at OC Transpo: without the interesting project and generous support they provided, this thesis would not have been possible. Finally I wish to thank Mr. Lule Chen for his help and suggestions.

Table of Contents

Abstract.....1

I. Introduction.....2

I.1 Literature Review.....3

I.2 Outline of the Research.....6

II. Background of the Research.....8

II.1 General Definitions.....8

II.2 Types of Bus Service Control Strategies.....10

II.3 Monitoring Technology.....22

II.4 Operating Environment at OC Transpo.....25

II.5 The Types of Bus Services.....28

III. Headway Control & Flexible Scheduling.....37

III.1 A Customer Survey.....37

III.2 Building Flexibility in the System.....50

III.3 Headway Control Using Flexible Scheduling.....56

III.4 Theoretical Effectiveness of Flexible Scheduling.....61

IV. Experimentation and Results.....68

IV.1 Experimental Situation.....68

IV.2 Statistical Basis for the Analysis.....72

IV.3 Analysis of the Distributions and the Number of Breakdowns.....73

IV.4 Analysis of the Results.....74

V. Development of User Interface.....97

V.1 Requirements of the Development of the User Interface.....97

V.2 Design of the User Interface....................101

V.3 Design and Development of the User Interface....................107

V.4 A Brief User Guide for the User Interface....................111

VI. Conclusion and Future Research....................113

VI.1 Summary of the Results....................113

VI.2 Some Implementation Issues....................113

VI.3 Future Research....................117

VII. Appendix....................118

VII.1 AVLC Modular Concept at OC Transpo....................118

VII.2 Public Schedule for Route 95 at OC Transpo....................119

VII.3 The questionnaire format for survey I (SET 1)....................120

VII.4 The questionnaire format for survey I (SET 2)....................121

VII.5 The questionnaire format for the final survey....................122

VII.6 Stops on Route 95 in the simulation model....................123

VIII. References....................124

Abstract

The critical criterion for evaluating a bus control strategy is how well it can improve the reliability of bus service. For high-frequency urban bus service, the service reliability is more a function of bus regularity than schedule adherence. Previous research has shown that headway control strategy is more appropriate for improving bus service with high service frequencies than the traditional schedule control strategy.

A customer survey has been undertaken to determine what is the largest headway, i.e., the time between the departure of two successive buses at stops of a given route, such that headway control strategy is still reasonable for bus control. Based on the results of our survey, the research of this thesis is focused on headway control when it is believed to be suitable.

Regularity of a given route for a given period of the day can be controlled through real-time actions aimed at maintaining adherence to the planned headway. While holding policies have been shown to be very effective in keeping the headway constant, they usually suffer from an inability to adjust quickly to the changing conditions along the route, such as buses breaking down, or not pulling out from the garage.

In this thesis, we propose an improved holding policy - "flexible scheduling" as a means for the buses along the route to auto-regulate themselves based on real-time data obtained through the Automatic Vehicle Location Control (AVLC) system, a technology that allows the controller to know the relative position of buses along the route.

The idea of flexible scheduling will be discussed in detail. Experimentation of this policy will be conducted on a simulation model. Results will be reported and analysed.

A user interface which provides easy access to both the simulation model and a control module is also developed to provide a better working environment to the users of these models.

Finally, conclusions and avenues for future research will be discussed.

I. Introduction of the Research

This thesis is focused on improving high-frequency bus service and providing better service to the public. The level of service provided is a function of the bus frequency, which is measured by the number of buses per hour. Usually, a high-frequency bus service is defined as a service level with more than 15 buses on one route per hour, which means service is available every 4 minutes (or less) if the buses are spread evenly. This research is undertaken with the collaboration of Ottawa-Carleton Regional Transit Commission (OC Transpo).

The most important and difficult problem faced in our research is how to better use existing technologies (including bus control strategies and system performance monitoring technologies) for improving service reliability through on-line controlling and dynamic re-scheduling.

The quality of bus service is evaluated by its reliability. By definition, ***service reliability*** is the invariability of service attributes which influence the decisions of travellers and transportation providers, and it is mainly measured by two types of indicators: indicators of ***regularity*** and indicators of ***punctuality*** [1]. In other words, the more regular and more punctual the service is, the more reliable it is. Research has also shown that service reliability is a function of the frequencies of service offered, and for high-frequency services, it is more important to maintain the service regularity than to concentrate on the service punctuality to provide and maintain a more reliable service [3].

In this thesis, we will study how on-line controlling, dispatching and dynamic re-scheduling can be applied to improve service reliability on high-frequency routes, and service regularity will be our chief performance indicator in measuring and evaluating control policies. In order to validate our hypotheses, a simulation model developed by the Canadian Institute of Guided Ground Transportation (CIGGT) and representing the running of OC Transpo Route 95 will be used. As described in [5], Route 95 is a very high frequency route operated by OC Transpo: it is the backbone of the transit network.

In order to meet the needs of their customers and to adapt to geographical constraints, most urban public transit agencies must operate a complex network of bus routes offering a wide variety of services. For such a complex network, a computer-aided control system (knowledge-based) is believed to be a useful decision-making support tool for the controllers. This is because, with a well developed knowledge-based control system, we can process more data and evaluate more control options at little or no additional real cost. It is also more efficient (i.e., faster, not error prone) for the computer-aided control system to do routine controlling and basic calculations than for human controllers, hence, less time will be consumed before a suitable control decision can be made.

Such a knowledge-based control system must be designed to include many relevant decision rules so as to provide effective control actions to the controller for a wide variety of situations. The system must suggest or even implement in real-time effective control actions based on on-line information about the current conditions in the transit network. This information would be obtained by radio, or directly through an Automatic Vehicle Location Control (AVLC) system, which allows the controller to know the relative position of buses along any route.

In order to program effective control actions inside the knowledge-based control system, it is necessary to first test their effectiveness: this can be done at little cost and with no disruption to the real transit system with the use of simulation.

In this thesis, we propose a new approach to real-time control of buses operating on a high-frequency route. This approach, which we refer to as flexible scheduling, is a control policy which dispatches buses of a given route from so-called "control points" so as to maintain actual headway constant, and that features the capacity of adjusting the headway dynamically as conditions along the route and in particular, the number of buses allocated to the route, changes. Through a simulation study, we shall evaluate the effectiveness of this approach which could eventually be integrated into a knowledge-based system.

Before we develop the idea of flexible scheduling, it is important to gain a good understanding of relevant literature in the field of urban transit service control.

Section I.1 Literature Review

The extensive study entitled "Synthesis of transit practice: supervision strategies for improved reliability of bus routes" by Levinson [13] was found to be a very useful reference in helping us to have an overall idea of how to improve public transit service by using suitable control strategies. The author pointed out that a reliable bus service involves maintaining regular headway, and keeping service variations to a minimum. The importance of these criteria typically depends on the service provided and thus on the type of bus route. Real-time monitoring, supervising and controlling of bus service are very important in providing and maintaining a reliable bus service.

Real-time bus controlling will not be possible unless information regarding the transit network (including the conditions on the routes, the locations of the buses along the routes, etc.) is made known on-line. Benefiting from the quick development in the system monitoring technologies in the past two decades, real-time service controlling is now playing a more and more important role in providing reliable bus service to the riders. However, as shown from our literature review, research on the development and evaluation of real-time control strategies aimed at maintaining the service regularity has been slow, since traditionally, punctuality was considered to be more important, and without sophisticated technology, service regularity was very difficult to measure in real-time.

There are two types of real-time bus control strategies, namely the headway control strategy and the schedule control strategy [13]. The most significant difference between these two control strategies is the criterion on which they are focusing: headway control strategy focuses on headway adherence, i.e., it seeks at maintaining constant headway between buses, while schedule control strategy focuses on schedule adherence, i.e., it seek at insuring that buses leave stops on schedule.

It is suggested that for high-frequency service, headway control strategy seems more appropriate in improving and maintaining the service reliability than the traditional schedule control strategy [3]. To confirm this, two headway control policies (threshold policy and "message board"policy) have been shown to be very effective with high-frequency service [5].

In order to monitor the bus service system and provide real-time information for service control, many transit properties have installed data collection systems to get information about the service performance and passenger usage. Two such systems are Automatic Passenger Counting (APC) system and Automatic Vehicle Location Control (AVLC) system. Previous experience has shown that these two systems are very useful [12][13]. Thanks to the help of Mr. Koffman and Dr. Gault at OC Transpo, many documents on the operating environment at OC Transpo were provided, including detailed information on APC and AVLC systems [16][17][18][19], the current available control policy in AVLC system at OC Transpo and updated schedules on Route 95. A more detailed survey can also be found in a master's thesis written by Lam [12].

The "Canadian Transit Handbook" [26] which discusses many aspects related to the transit industry, including history of the industry, general definitions, classifications of transit technology, methods of designing a customer survey, etc., was very useful in providing definitions and clarifying concepts for our research.

Literature about other relevant transit information systems, such as Geographic Information Systems (GIS) [24], and Passenger Information Systems (PIS) (which provide scheduled and updated information to the passengers) [12] has also been reviewed so as to acquire a better understanding on how the system information is obtained and how it can be used.

To make better use of APC and AVLC information in service planning and real-time bus control, OC Transpo has commissioned the development of a simulation model to simulate the movement of buses along a given route. This simulation model is designed to be capable of connecting with the AVLC system to update its simulating dynamically according to the changes in the relevant AVLC data files, so as to simulate the real performance of a given route. Therefore, a controller could test the effectiveness of an action with the simulation based on real-time information before implementing the action in the real system. Such a real-time capacity is not yet functional however. The simulation model was built up flexible enough to be adapted to any bus route, but in our version (OPSSIM 1.00) of the simulation model at the University of Ottawa, only the relevant data files of OC Transpo Route 95 were available (including distances between stops, travel time distributions, passenger arrival rates, etc., which were obtained from APC data files). The specification and the user manual of the simulation model [6] was a very helpful documentation to help us to understand this simulation model. In addition, a control module was developed for the purpose of testing some real-time service control policies during the running of the simulation model. Details on the development of this control module can be found in [5].

For the purpose of better using the simulation model and the control module, and of developing a user-friendly interface to the users, some other applications using knowledge-based systems in public transportation were reviewed [7][8][25][27], including the Intelligent Vehicle Highway Systems (IVHS) [14] (the goal of IVHS is to apply advanced electronics, computing, and communication technology to improve highway efficiency and safety). "A synthesis of knowledge based expert systems in transportation" authored by Louis Cohn and Roswell Harris [7] gave us an overall view of the use of knowledge based expert systems (KBES) in transportation. It covered the history of the development of KBES, current applications, potential applications in transportation, and the KBES architectures. Although these KBESs were different from what we are hoping to develop, they still helped us to obtain a better understanding of the common characteristics of knowledge-based systems and also provided us a good guide in expanding our control module by adding new control policies.

The ultimate goal of our research is to expand the control module into a knowledge based expert system capable of analysing a given situation, and, based on knowledge acquired by experience and experimentation, choose the most appropriate control action(s) to rectify the situation and improve service. In this thesis, one headway control policy has been added into the control system: more work will have to be done in the future to reach this goal.

The language used for the programming of the control module is Prolog. This is because the existing control module was developed in Prolog, and Prolog is a very powerful language for building knowledge-based systems. [4]

Section I.2 Outline of the research

The main purpose of this thesis is to develop a new headway control policy -- flexible scheduling, then test it and evaluate it. The thesis consists of six chapters. This first chapter is an introduction of our research work.

In chapter II, we provide the background and motivation to our research. Concepts and terminology specific to the urban transit industry are defined. We present the current situation at OC Transpo which motivated this research. We outline the various types of bus service control strategies available to public transit agencies and the various types of bus routes. We discuss the role and importance of monitoring technology and present critical issues to be considered in locating on-street bus detectors.

Chapter III is the most important chapter of the thesis research. It focuses on the development of a new headway control policy -- flexible scheduling. It is composed of two sections: description of the flexible scheduling policy and development of an analytical argument used to demonstrate the potential effectiveness of the policy using a simplified model. This chapter will also report on a survey of a sample of passengers performed to identify what is the lowest service frequency such that headway control would be preferred to schedule control as on-line service control strategy.

In chapter IV, the simulation experiments will be discussed, and the simulation results will be analysed: we will evaluate the effectiveness of flexible scheduling against the threshold headway control policy, which is the simplest headway control policy.

The research in Chapter V focuses on the design and the development of a menu-driven user interface to make the existing simulation and control module much more convenient to the users. Before this user interface was developed, all the operations on the computer had to be done manually, which made it difficult for the users who were not familiar with Sun work stations, the UNIX operating systems and how the control module was developed to work on the simulation model and the control module.

The last chapter (chapter VI) will give a conclusion of our research and discuss possible future works in the relevant areas.

II. Background of the Research

The purpose of this chapter is to provide the background and motivation to our research. In the first section, general definitions specific to the urban transit industry and relevant to our research will be given; service control strategies and policies will be defined; monitoring technology available to and used by many transit agencies will be described. The current situation at OC Transpo will be portrayed, focusing on the development of their monitoring technology and on recent research initiatives on on-line service control. A brief description of the research of Lule Chen will also be given.

The various types of bus routes will be presented to conclude this chapter.

Section II.1 General Definitions

The ***schedule*** is the predetermined timetable specifying the departure time of each trip at a subset of stops on a given route. It is usually fixed and made available to the drivers (to help them to regulate the departure time from a subset of the stops along the route) as well as to the passengers (to help them to plan when to head towards the stops so as to reduce their waiting time at the stops). A ***block*** represents the full schedule of a bus from garage pullout to garage pullin on any given day (i.e., the complete list of trips along with departure times) [21]. One block is usually carried out by one bus (not necessarily by one driver), and is usually assigned to one route (i.e., all trips carried by one block will be listed belonging to the same route), unless interlining is involved (see section II.1.4).

Schedule adherence represents the degree to which bus departures from a given stop conform to the schedule, and is an indicator of service punctuality. As it is almost impossible for buses to run precisely "on time", the schedule adherence is measured in relation with the ***trip schedule adherence tolerance parameters***. For example, if the trip schedule adherence tolerance parameters are set to one minute for earliness, and three minutes for lateness, then a bus is defined to be "**on time**" if it leaves the stop no more than one minute earlier or three minutes later than the scheduled departure time. Research has shown that buses running "early" are worse than buses running "late" [1].

The ***headway*** is defined as the time between the departure of two successive buses of a same route from a given bus stop [5]. In general, the ***planned headway*** represents the scheduled frequency of the service (also known as the level of service) provided to the public: it indicates the scheduled number of minutes between consecutive buses on a given route. Usually, for a certain period of a day (e.g., peak period) on a given route, a planned headway will be predetermined and will not change over that period. Schedules are derived based on the level of service the transit agency wishes to offer, i.e., based on the planned headway.

Headway adherence represents the degree to which the actual headway at a given stop conforms to the planned headway, and is an indicator of service regularity. It is measured by the difference between the planned headway and the actual headway at a given stop for each bus. Headway adherence is most important and relevant for high-frequency service.

Bus service reliability is defined differently, depending on the planned headway. Previous research has shown that for short planned headway (i.e., high-frequency service) periods, the service regularity is the most important indicator of service reliability [1]. In this case, the ability to maintain a constant headway (i.e., headway adherence) is crucial in achieving reliable service. For low-frequency service, the passengers will tend to check the schedule before heading to the stops: hence the punctuality of the service becomes essential, and the ability to adhere to the schedule is the most important characteristic of reliable service.

Interlining and intralining are two important scheduling strategies used at some transit agencies (including OC Transpo). It is important to understand the distinctions between these two strategies before applying any real-time control policy.

Interlining is a scheduling strategy aimed at producing operating efficiency (i.e., minimizing the number of blocks needed to provide the planned service level) by assigning to blocks consecutive trips on different "compatible" pairs of regular routes. For example, suppose the departure terminal and the destination terminal of two different regular routes are the same in each direction. Given the scheduled trip time and the planned headway for these two routes, it would be possible that 1.5 buses are needed on each route to cover the planned service level. Without interlining, the transit agency would have to allocate two buses to each route. However, by creating a loop joining the two routes, it may be possible to allocate only three buses, shared by the two routes, to cover the planned service level: this illustrates the use of interlining among "compatible" pairs of regular routes. Interlining is also frequently used during the peak period, when service levels are increased and more buses are needed, so that a large interlined network may be created. Interlining also tries to reduce the number of non revenue kilometres (distance travelled between two terminals while the bus is out-of-service) by trying to assign to a bus completing a trip on a given route at a given stop, a second trip that would start shortly after the previous trip ended, and as close as possible from the location of the bus when it completed its trip. In this case, buses may not come back to their original route again.

If interlining is used, buses may be asked to deadhead during their service period, which means they must leap from one stop to another stop (possibly on another route) without stopping or providing service. ***Deadheading*** is a non revenue time period given that the buses do not provide service to the public during this period.

Intralining is a method of assigning a block with consecutive trips on the same route [21]. This is the most widely used method in scheduling: in this case, consecutive trips of a same route are assigned to a block with a short amount of time between two trips. This time buffer between trips serves two purposes: ***service recovery time*** which is the time allocated to the drivers in case his previous trip ran late so that his following trip can still start on time, and ***layover time***, which is a short break time for the drivers.

The usage of interlining and intralining is a function of the type of bus service (or bus route). For OC Transpo Route 95, interlining is not used: this is also true for most mainline routes (see section II.5.2) during their high-frequency service periods. Therefore, for high-frequency service in our research, we will not need to consider the impacts of interlining.

Section II.2 Types of Bus Service Control Strategies

Although our research will be mainly focused on headway control strategy, it is important to have a clear understanding of all the control strategies, and especially to realize which control strategy is the most suitable under a given situation.

In bus transit systems, a ***control strategy*** can be defined as a set of control policies driven by a specific objective and used to rectify various adverse consequences resulting from a given incident. In other words, a control strategy is used to address a given problem (eg. major service disruption caused by an accident, or headway deviation, or schedule deviation) so as to attain a specific service objective. As many unfavourable consequences may result from a given problem, more than one action or policy may need to be applied to resolve these consequences. From literature review, we denote four types of bus control strategies, namely the ***schedule control strategy***, aimed at keeping close adherence to schedule, the ***headway control strategy***, aimed at minimizing deviation from the planned headway, the ***service restoration and recovery strategy***, aimed at returning to the planned service level following a major disruption such as a breakdown, an accident or a major traffic jam, and the ***passenger loading and alighting control strategy***, aimed at relieving the problem of delays and overload at major passenger boarding points.

A bus ***control policy*** is a set of control actions aimed at resolving a problem (or problems) in a specific way.

As most control policies may be used as part of more than one control strategy, we first define the most common control policies:

▪***Add an extra*** means to assign an extra bus to a route to add a trip(s) to increase the current service capacity. The application of this control policy is highly dependent on the location of the extra bus and where the extra is needed;

▪***Short-turn*** requires a bus to cut short its current trip, and head back in the opposite direction. It is a real-time control policy, and can be applied quickly if needed. The application of short-turning will have an impact on the passengers still on board who wanted to travel further along the route;

▪***Switch trips*** consists in having two buses operating on the same route to exchange their scheduled trips. This may apply when a given bus is unavailable (or late) to take on its scheduled trip, while a second bus assigned to the same route is available and waiting to start its (later) trip: the controller may ask the second bus to take the place of the missing bus: when the late bus arrives, it will be assigned the trip left open: in effect, the buses have exchanged trips, and the service level can be maintained. Switch trips can be used as a planning or a real-time control policy, and it may have an impact on the following trips of those buses that have exchanged their trips if they are interlined;

▪***Create a shuttle service*** is a service control policy whereby an ad hoc loop service is implemented in order to maintain the planned service level. It may be required to respond to major service disruptions, such as serious accident involving the bus. However, considering the extra cost, this policy is used only when an emergency occurs;

▪***Fill in from another route*** is only used for the current day as a real-time control policy, and can be defined as using a vehicle from one route to cover a trip on another route in order to maintain the planned service level on the second route. The application of the policy depends on the position of the vehicle and location of the route;

▪***Fill in with an extra*** means to assign an available extra to cover a planned trip. The difference between this policy and adding an extra is that fill in with an extra is aimed at maintaining the planned service level, while adding an extra is aimed at increasing service level. It depends on whether there is an available extra, and also on the position of the extra with respect to where it is needed;

▪***Skip stops*** is a commonly used policy to save travel time by skipping certain stops. It is most practical when the bus is running late: it can only be applied if no passenger wishes to drop off at the stops the driver intends to skip. It creates dissatisfaction to those passengers waiting for the bus at the skipped stops. Therefore, it is suggested to be used only on high-frequency routes so that the waiting time of those passengers is minimized;

▪***Temporary re-schedule*** is a scheduling method used to adapt the schedule to the changes in the available resources (i.e., the number of available buses on a given route). It may affect a period of day to several days. When this re-scheduling is done dynamically, it is defined as flexible scheduling;

▪***Hold a bus*** can be applied when the bus is running early according to either schedule adherence or headway adherence. Thus, holding a bus can be used for both headway control and schedule control purposes. Holding a bus will have an impact on those passengers already on-board.

Two headway control holding policies are available in the control module developed by Chen [5], they are:

①***Threshold*** policy, where at chosen control points, the arriving bus will be delayed if and only if the headway between this bus and the previous bus is less than the preset threshold value (which is usually equal to the planned headway). This is a real-time control policy;

②***Message board*** policy is an improved threshold policy, such that if the headway between bus i and the previous bus, i-1, is greater than the planned headway, a delay message will be sent forward to i-1 such that the headway between i and i-1 and the headway between i-1 and i-2 are equal.

Clearly, situations will be more complex in a transit network with interlining than without interlining, because the application of a control action on one bus on the current route may affect other routes and even the whole system if this bus is assigned to interline with trips on other routes. For example, if we hold a bus for headway adherence or schedule adherence on it's current operating route, this action may improve the service reliability for the current route, but it may also unexpectedly delay this bus to take on its following trips on other route(s): therefore, the control action may create problems for other route(s).

We now provide a more formal description of the four types of bus service control strategies.

II.2.1 Schedule Control Strategy

DEFINITION

A set of control policies aimed at maintaining schedule adherence. The objective of schedule control strategy is to "push" off-schedule buses (either early or late) back to the planned schedule.

PROBLEMS ASSOCIATED WITH SCHEDULE ADHERENCE

Problems associated with poor schedule adherence are buses running "early" or "late", and missed trips.

Trip schedule adherence tolerance parameters are used to determine whether a trip, for a given day, is to be considered off-schedule. A trip is considered to be off-schedule when the difference between actual running time compared to the scheduled time are beyond the trip schedule adherence tolerance parameters [21]. For example, if the trip schedule tolerance parameters are defined as [-2, +5] minutes, then buses running less than 2 minutes early or no more than 5 minutes late are concerned "on time": otherwise, the bus is either running "early"or "late", and some schedule control actions may need to be applied. At OC Transpo as well as in the simulation model, the trip schedule adherence tolerance parameters are set as [0, 3] minutes.

CONSEQUENCES OF THE ABOVE PROBLEMS

▪When a bus runs early according to its schedule, some passengers may miss the bus even if they check the schedule information and head to the stops accordingly, and they may have to wait even longer than the planned headway. If the planned headway is long (eg. 30 minutes), these passengers will have to endure a long waiting time. If the bus is running early, and the following is "on time" as scheduled, a longer gap will be created between the "early" bus and the following one, which may cause heavier passenger loading on the following bus;

▪If a bus runs late, the average passenger waiting time associated with this bus will be longer, and there is a risk of missing transfers;

▪If a scheduled trip is missed, passengers who are expecting that bus will have to endure longer waiting times at the stops and heavier load may be created on the following buses.

PERFORMANCE MEASUREMENTS

▪Schedule adherence: % of buses early, on-time (inside the trip schedule adherence tolerance range) and late at chosen stops and for chosen periods of time, average earliness, average tardiness and absolute deviation: by how many minutes buses are early or late on average;

▪The range of the trip schedule adherence tolerance will affect the service reliability: a tighter range will imply more control actions in order to meet the more demanding requirements;

▪The distribution of the trip travel time (mean, standard deviation) can help to improve the schedule, so as to improve the performance according to the schedule. For example, if evidence shows that the schedule trip travel time is longer than what is actually needed, and a high percentage of buses run early because of this longer planned trip travel time, a more suitable (shorter) trip travel time should be used in the schedule to improve the schedule performance, and schedules should be adjusted accordingly;

▪The number of buses or trips added and cancelled on a certain day for the purpose of schedule control actions is also an indicator to evaluate the schedule performance.

SUITABLE CONTROL POLICIES

Schedule control strategy is the traditional and most easily implemented control strategy. Since each driver has a schedule on hand, it is possible for him or her to make some adjustments to try to keep the bus running "on time".

■FOR THE DRIVERS

▪Skip stops when no passenger wants to alight if the bus is late according to the schedule;

▪Speed up if the bus is late, or slow down or wait at a stop if the bus is early.

■FOR THE CONTROLLERS

▪Add an extra to increase the service level when there are extra demands: for example, during the period when the heavy usage of school students creates overloading and longer boarding time, an extra may be used to increase the service capacity, so that the schedule adherence may be improved;

▪Short-turn the buses when they are running late;

▪Deadhead the bus to a point further along the route when the bus is late;

- Holding the bus at certain stops for a short period of time when the bus is early;
- Fill in the trip with an extra or bus from another route when a bus breakdown occurs or when the bus is running too late or too early, or when there are many people waiting for the buses on a given route;
- Switch trips;
- Temporary re-schedule, the new schedules should be made available to the drivers as well as to the passengers.

II.2.2 Headway Control Strategy

DEFINITION

A set of control policies aimed at addressing problems related to headway adherence. The objective of headway control strategy is to keep the planned service level by spacing the buses on a given route in order to obtain a constant headway between successive buses.

PROBLEMS ASSOCIATED WITH HEADWAY ADHERENCE

Service irregularity is the main problem associated with headway adherence. The headway between two successive buses may be longer or shorter than the planned headway.

CONSEQUENCES OF THE ABOVE PROBLEMS

As the planned headway gets shorter, the passengers tend to be not conscious of schedules, and they just head to the stop randomly, thus their arrivals can be modelled as a Poisson process [15], and the following formula [29] can be used to calculate the passengers' Average Waiting Time (AWT):

Formula II.2.1 ***Passenger Average Waiting Time (AWT) for the passengers waiting at the stops along the route given a Poisson Passenger Arrival Process:***

$$AWT=\frac{\sum h^2}{2\times\sum h}=\frac{\bar{h}}{2}(1+\frac{S.D.(h)}{\bar{h}})^2$$

Where:

$\bar{h}$= the mean of the observed headway;

S.D.(h) = the standard deviation of the observed headway.

We can see that the irregularity (S.D.(h)) in the headway will cost longer AWT than the minimum value, which is half of the planned headway, if the actual headways are perfectly regular (e.g., SD(h) = 0).

Furthermore, when headway is irregular, bus bunching and bus overload may result. Bus bunching occurs when a bus of a given route catches up to its predecessor (on the same route): this usually implies a large gap between two buses, which implies more passengers are boarding on the second bus, creating bus overload problems.

PERFORMANCE MEASUREMENTS

- The mean and standard deviation of the actual headway;
- Average Waiting Time (AWT) of passenger at chosen stops;
- Waiting factor (by using the planned headway), which is defined as:

Formula II.2.2 ***Waiting factor (WF) for the passengers waiting at stops along the route***

$$WF = 2\times(\frac{AWT}{hp})\times 100\%$$

Where:

AWT = the average waiting time of the passengers waiting at the stop;

hp = the planned headway.

The waiting factor WF is a performance measure indicating how well the planned service has been provided. The ideal value of WF is 100%, where the planned headway has been kept perfectly (i.e., S.D. (h)=0). We will use this indicator in our future tests and argue that service has improved if WF decreases.

- % of passengers waiting longer than the planned headway at each chosen stop. In order to provide a good service, this indicator should be kept as small as possible;
- The number of buses or trips that have been added and cancelled on certain date for the purpose of headway control action.

SUITABLE CONTROL POLICIES

Unlike the schedule control strategy, headway control strategy is a relatively new strategy in bus control, and it is more difficult to implement compared to controlling buses according to an available timetable as is done in the schedule control strategy. Technologies for real-time performance monitoring are essential in applying headway control policies. It is not possible for the drivers to individually take any actions when headway control strategy is applied, unless they are made aware of the information about the position of the preceding and following buses. It is more appropriate to use some knowledge-based system to analyse the situation and to assist the controllers to make the most effective decisions.

The threshold holding policy is the most used policy in order to keep the headway constant, and to achieve the smallest AWT for the passengers waiting at the stops along the route. However, holding the bus will increase the travel time of those passengers already on the bus. This has been studied by Turnquist and Blume [28]. They gave the following figure to identify this problem based on their theoretical study:

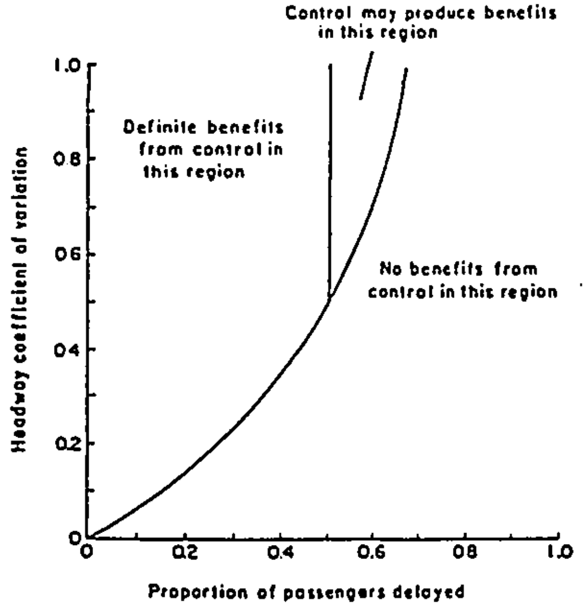


Figure II.2.1 Range of usefulness of headway control using holding policy

The above figure indicates that the "major incentive for making the headway more regular is to reduce waiting time of passengers who board at or beyond the control point". The authors suggested that it would be desirable to control a route at a point where relatively few people were on the bus and many were waiting to board at subsequent stops.

Other suitable control policies for headway control include:

- Message board holding policy;
- Fill in with an extra or bus from other routes to keep the planned headway level;
- Adding an extra to create excess capacity in the system to improve the headway adherence, this will be explained in section III.2;
- Keep the time interval between buses by deadheading, short-turing, speeding up, or skipping stops;
- Short-turn buses;
- Switch trips;
- Cancel trips (full or part of a trip);
- Flexible scheduling policy may apply when the available resources change (for details see section III.3).

II.2.3 Service Restoration/Recovery Strategy

DEFINITION

A set of control policies aimed at recovering the service from major disruptions. The main objective of this control strategy is to try to maintain the planned service level when major disruptions occur, and to try to minimize the duration of these disruptions, so as to minimize the adverse impact of those disruptions on the service.

PROBLEMS ASSOCIATED WITH SERVICE DISRUPTIONS

Whenever there is a major disruption such as bus breakdown, bus accident, blockade due to accident not involving the bus, the service will suffer accordingly, so that service restoration/recovery strategy should be applied.

CONSEQUENCES OF THE ABOVE PROBLEMS

- Possible lateness or cancellation of the remaining part of the current trip and of future trips that are assigned to that bus/operator;
- Delay for passengers on board and downstream, which is a function of the planned headway and the types of bus route (definitions of the types of bus route will be given in section II.5). For example, if the disruption happens on a mainline route, passengers may transfer to another bus

route going in the same direction. On the other hand, if the disruption happens on a local route which has no connection with other buses, the passengers have to wait until the next bus on the same route comes. It seems more necessary for the application of service restoration/recovery strategy in the second case since the headway is usually long for local routes. For mainline and express/limited stop routes (section II.5), more consideration should be given to the recovery of the interlining schedules in order to minimize the impact of the disruption on the interlined network;

▪Possible bus overloads, as the following buses pick up more passenger left waiting because of the disruption.

PERFORMANCE MEASUREMENTS

▪How quickly the service can be recovered to the planned level;

▪How many extra resources are used to recover the service to the planned level.

SUITABLE CONTROL POLICIES

1▪Add an extra;

2▪Switch trips (if applicable) until this disrupted bus can be placed back in service;

3▪Fill in with an extra or bus from another route to cover the remaining part of the trip after a bus breakdown occurred;

4▪Replace a defective bus with a properly functioning bus which is pulling in (using the same operator);

5▪Switch trips;

6▪Create a shuttle service under an emergency situation;

7▪Leave this disrupted trip as it is (let next bus to pick up the passengers left waiting), and try to recover the following trips.

The position of the disruption on the route is very important in applying the suitable policies. For example, if a bus breaks down at the beginning of the trip, some control actions will usually be necessary, since all the passengers waiting for this bus along the route will be affected by the breakdown if no control action is taken. On the other hand, if the breakdown occurs close to the end of the trip, and no extra resources are currently available, it may be wiser to just cancel the remaining part of the current trip (i.e., let the following bus pick up the passengers from the broken down bus), and try to have an extra to fill in for the next trip.

The following table is just a simple grouping of the control policies we presented above (the numbers shown in the table are associated with the control policies), in which:

A represents the type of the bus routes, which will be defined in next section;
B represents the location on the route where the disruptions occur.

Table II.2.1 The impact of the position of the disruption on the control policies

B A	beginning of the trips	middle of the trips	end of the trips	at the middle of two distant stops
local routes	1, 4	6	2, 6	6
mainline routes, headway<15 min	1, 3, 4, 5	3, 5	2, 7	3, 5, 7
mainline routes, headway≥15 min	1, 3, 4	1, 3, 5	2, 6	3, 5, 6
express/limited stop routes	1, 3, 4, 5	3, 4, 5	2, 3, 5, 7	1, 3, 4, 5, 7

II.2.4 Passenger Loading and Alighting Control Strategy

DEFINITION

A set of control policies aimed at solving the problems of delays and overloads at major passenger boarding points. ***Overload*** occurs when there are more passengers than seats in the bus (i.e., some passengers are left standing in the bus). The major objective of this strategy is to provide a comfortable service to the passengers, and reduce the service deviations.

PROBLEMS AND CONSEQUENCES

While the passenger overload is one of the consequences of lateness, it also causes lateness in the operation of the buses.

PERFORMANCE MEASUREMENTS

- % of passengers standing on buses on a chosen route;
- Number and percentage of trips which are overload, ***revenue KM*** (which can be defined as part of the kilometres travelled by the bus while it is providing service to the public) of overload, revenue hours of overload of a chosen route;
- Average passenger loading and alighting time at a chosen major passenger boarding point.

SUITABLE CONTROL POLICIES

- Fill in with an extra or bus from another route to solve the overloading caused by bus breakdowns;

- Add an extra bus to increase the service capacity to resolve the overloading;
- Switch trips, for example, with the high-frequency service, one bus can be switched to pass its previous bus if the previous bus is heavily crowded.

We know that, for a bus transit network, there are many internal and external factors that affect the normal running of the buses, which makes the operating conditions very complex and variable. For example, the driver may face many different and difficult situations while he is operating a bus, such as traffic congestions, bus breakdowns, bad weather conditions, construction along the route, schedules which are either too tight or too loose, not counting the variability in his own driving performance. It is obvious that he cannot possibly operate the bus on the same route exactly the same way from day to day or from trip to trip, because many of the above situations are not under his own control.

Therefore, it is very important for the transit agencies to apply some control strategies to handle the unexpected situations in order to try to provide and maintain their planned service levels. Controllers always try to find and use the most suitable control strategy for a given problem. It is very important for them to choose the most suitable control strategy, because a misused control strategy may not be as effective as expected, or, it may make the situation even worse: hence, poorer service may result.

In the real system, if an inappropriate control strategy (or policy) has been applied to address a problem, it may take the controllers some time to realize and correct the error. Furthermore, even if the controller identifies the correct control action to take, the reaction time is usually not immediate. This motivates research in identifying the effectiveness of control strategies and policies given specific situations before they are applied in the real system. Theoretical and analytical developments, together with computer simulations, are effective ways for evaluating different control strategies and control policies.

Certain control policies may be applied almost immediately (e.g., holding policies, which consists in holding a bus at certain stops when it is running early), while others may require more time (e.g., adding an extra bus to fill in for the trips left by a broken down bus). Hence, in identifying a problem, it is very important to know how much time we have to apply a policy, which is often a function of the location of the buses on the route (the beginning, the middle or the end) when the incidents occur. This makes the monitoring techniques very important in bus transit systems, especially for on-line controlling and dynamic reactions.

Section II.3 Monitoring Technology

Service reliability can be improved either through better planning of the operations, which can result in the development of better schedules for example, or through improved real-time control, which implies reacting more quickly and more effectively to incidents as they occur. Therefore, data on daily operations must be collected to be analysed off-line, in the case of service planning decisions, or on-line, in the case of dynamic bus service control. Monitoring technologies have thus been developed to support these two needs.

Currently, there exists a few different types of systems for monitoring service operation on the urban transit network. The two most broadly used systems (both are available at OC Transpo, thus are also very useful for our research) are: Automatic Passenger Counting (APC) system and Automatic Vehicle Location Control (AVLC) system.

II.3.1 Automatic Passenger Counting Systems

In order to overcome the problems associated with manual data collection techniques, ***Automatic Passenger Counting (APC)*** systems were first installed in some cities in North America and Europe in the 1970's, progressively updated in the 1980's and are now well developed. Basically, the systems can monitor and provide basic information on vehicle location, number of passengers boarding and alighting, and travel time [12][13].

APC systems are essentially planning tools, and the off-line report-oriented information on almost every performance measure of bus service provided by APC can be used for service analysis, schedule development, transit planning and management, and marketing. Although APC data are not real-time based, APC systems are still the essential planning tools in improving bus services. For example, the data concerning the passenger behaviours (e.g., the passenger arrival rate at stops) in the simulation model used in this research were generated using APC reports. These data will be used to simulate the real system and determine the effectiveness of the control policies.

II.3.2 Automatic Vehicle Location and Control Systems

Given the increasing needs for real-time surveillance and better on-line controlling of bus service, the implementation of ***Automatic Vehicle Location and Control (AVLC)*** systems began to receive real attention in the late 1980's. This coincided with the quick development of relevant technologies, such as telecommunication, computer science, and detecting techniques, which offered new opportunities for the application of real-time bus control strategies and also for the off-line service analysis [12][13].

While the data collected by APC systems are usually recorded by onboard devices and are analysed on an off-line basis, the data generated by AVLC systems can be used in real-time, and are obtained either by detectors located along the bus routes or by polling on-bus computers. As an example, the AVLC modular concept at OC Transpo is represented in ***appendix VII.1***. For details about the modular structure and the system concepts, please refer to [13][17].

As more APC, AVLC and other kinds of monitoring systems (i.e., the Geographic Information Systems (GIS) as we mentioned earlier) are being implemented by different transit agencies, the need for better use of the information provided by these systems to improve service reliability has grown.

The effectiveness of real-time control policies is dependent on the quality of the information available, and this depends on the number and location of AVLC detectors.

II.3.3 Locating AVLC Detectors

There are at least four types of detectors installed within AVLC systems [20], they are:

▪***Control point detectors*** provide information required for service control, and should be strategically located to maximize their usefulness and effectiveness in the bus service control;

▪***Public information point detectors*** use the location of passing buses as an input for public information on-street signals, and should be located to optimally serve the requirements of the on-street public information system;

▪***Garage exit/entrance point detectors*** monitor and report the movements of vehicles into and out of the garages;

▪***In-garage parking detectors*** support the requirements of the equipment division for managing the positioning of buses inside the garages.

Some other data collection point may need ***additional detectors***, which should be strategically located to collect information for improving the quality of future schedules.

Given the high cost of purchasing and installing the detectors, it is not possible to have many detectors along every route; furthermore, having too many detectors may create additional problems such as information overloads. For these reasons, it is important to locate the available detectors carefully. The problem of locating detectors has not been well documented in the literature. From the literature review, our research, and consultation with OC Transpo, we found many factors are important in determining the location of AVLC detectors: the most important of these factors are discussed briefly below. This topic is not the major focus of this thesis research, so only a brief introduction will be given.

TWO MAJOR OBJECTIVES IN LOCATING AVLC DETECTORS:

- To minimize the total costs for both short term and long term. The costs include equipments, installation and maintenance of detectors, movement and reinstallation of detectors if needed, the costs for data collecting, organizing, analysing and storing, and other costs relevant to the specific location of the detectors in the AVLC system;
- To obtain useful and sufficient real-time and off-line information for taking bus control actions without information overload [20].

A WELL-LOCATED DETECTOR SYSTEM SHOULD HAVE THESE CHARACTERISTICS:

- To ensure that the information provided will allow sufficient time to the controllers to decide on and to implement appropriate control actions(ahead of the points at which control actions are likely to take place);
- To ensure that the information will be provided on as many different routes as possible (such as major transfer points);
- To ensure that all buses passing by will be detected (avoid obstacles such that a bus would fail to be detected, such as traffic light intersections, bus stops beside more than one lane roads and roads with shoulders that allows for stopped vehicles);
- To be effective (i.e., choose the point without underground clearances including Hydro, Gas, Bell, etc.) and economic (e.g. some structure exist on which the detector could be installed).

Besides the above management and operational considerations, some other technical and physical factors also have impacts on the effectiveness of a detector system. More details are in [20].

Section II.4 Operating Environment at OC Transpo

II.4.1 OC Transpo

Ottawa-Carleton Regional Transit Commission (OC Transpo) is one of the biggest transit agencies in Canada. In 1992, it had 2203 employees, operated 138 routes covering the Ottawa-Carleton region, and the annual ridership served by OC Transpo was 78.6 million passengers in 1992.

Out of its 825 buses, 80 have been equipped with ***APC*** hardware and software. The APC system at OC Transpo has been recognized as "one of the better documented APC efforts" [13]. The system was first installed in 1976 and updated progressively in the 1980's and is now well developed at OC Transpo. The goal of APC system is to incorporate a real-time passenger counting capability, and to make this information available to the central control [13]. The APC system has allowed OC Transpo to collect detailed data on a more frequent basis than the previous manual collection system. It was proved to be a cost-effective system. APC also allows OC Transpo to tailor the services better to meet the passenger's demands [12].

At OC Transpo, an ***AVLC*** system has been under development since the late 1980's, and switched into usage earlier this year. Tests and evaluations have been done by phases (eg. testing of the equipment, evaluating of the AVLC data by comparing them with field observations, comparing of the actual AVLC data with planned criteria, etc.), and have shown this AVLC to be a highly effective and efficient system. This fact also exemplifies a successful application of this technology [12][13][18][19].

As part of AVLC system, the OC Transpo ***"560" system*** is a computerized public telephone information service system, which provides the users with the scheduled arrival time of the next two (or three) upcoming buses at a chosen stop. Within this "560"system, each bus stop of OC Transpo is associated with a 4-digit number, and when a customer dials "560" plus the 4-digital number, the schedule information regarding the upcoming buses at the chosen stop on a certain route will be provided. The passengers can call the "560" number to check the schedules from the telephones installed at major bus stops, or from home. Sometimes other information, such as delays due to weather conditions or bus breakdowns, will also be given. This "560" system has been used very broadly in the Ottawa-Carleton region as shown by a recent survey undertaken by OC Transpo, and it has also helped increase the ridership[12].

Interlining has been used as a method of optimizing the operating costs of the transit network at OC Transpo [23]. At OC Transpo, a large interlined network has already been built up, within which the schedules are set up by computer-aided optimization using interlining techniques and software. Given a planned schedule which lists all the trips required on each route in the transit network along with the trip start time, trip end time and the departure time from a subset of the stops along the routes, the computer system can calculate the minimum number of buses (or blocks) needed to cover all the trips for the entire network while meeting the schedule constraints through interlining. In order to achieve this objective, certain buses will be assigned consecutive trips on different routes, therefore, interlining applies. At OC Transpo, this interlined scheduling will be done every three months to keep the schedules up to date. Since some of the buses are interlined, it is important to realize that a control action on the current route may have repercussions on some other routes if the bus is interlined. In that case, we must consider the effectiveness of the control actions not only on the current trip and current route, but also on the following trips on some other routes so that the performance of the whole interlined network could be optimized most efficiently.

Extraboard management is used to cover assignments of operators who do not report in and to provide required, but unscheduled work, such as missed trips and bus breakdowns.

At OC Transpo, extra buses and operators are made available as extra capacity in the system to handle unexpected system disruptions, and they are always considered as the first option in order to minimize the extra costs. For a simple example, in case of a bus breakdown, the controller will assign an extra (if there is one available) to fill in the trips left by the broken down bus rather than book another regular driver. More details about the extraboard personnel scheduling and extraboard management can be found in reference [9]. There are two types of extra drivers at OC Transpo:

•A ***booked extra driver*** is the operator who is on board of a standby extra bus, and is strategically located to respond to service irregularities. They get paid as regular drivers;

•An ***overtime extra driver*** is an operator who, after completing a normal on-street assignment, is extended at an overtime rate to become an available resource and receives specific work assignments from control staffs.

Since overtime extra drivers will get paid at an overtime rate, which is one and a half times the regular rate, it is preferable not to use this resource, and the booked extra driver should be used first if needed. At OC Transpo, if the driver works between seven hours and 36 minutes to eight hours a day, he will be paid for eight hours at a regular rate. If the driver works an extra half hour after eight hours work, he will be considered as an overtime extra and will be paid at an overtime rate. The drivers are not required to work more than eight and a half hours for one day. However, they may be required to complete at most one more trip on their route (paid at overtime rate) after the end of their regular shifts if the relief driver is not available, for example.

II.4.2 The Simulation Model and Lule Chen's Research

As we mentioned earlier, most of the information used in our research is provided by the APC and the AVLC systems at OC Transpo. Based on this information, a simulation model (OPSSIM OC Transpo Transit Simulator) has been developed by the Canadian Institute of Guided Ground Transportation (CIGGT) for OC Transpo, for the purposes of developing and evaluating control actions.

The simulation model may be used to simulate any bus route, but is now programmed to simulate OC Transpo Route 95. Route 95 is the backbone of the transit network operated by OC Transpo.The most significant characteristics of Route 95 are as follows:

•High frequency service (short headway);

•High coverage of the ***Transitway***, which is a roadway dedicated to OC Transpo buses. Except in the downtown area and between Blair Station and Place D'Orléans, Route 95 is fully operated on the Transitway, which allows for higher average operating speed and better service reliability than those routes that are mostly operated on arterial streets;

•Full coverage of the Transitway stations on the East-West section of the Transitway network. In this way, Route 95 links most of the other mainline routes and local routes together because most of them also stop at one or more of these Transit way stations.

The first version of the model (OPSSIM 1.00) was developed for the VAX system used at OC Transpo, and was completed in 1992. The model was ported to a Sun SPARC ELC work station running UNIX by Chen [5]. It is now operated at the undergraduate laboratory of the Computer Science Department at the University of Ottawa. The newest version adjusted to comply with the OC Transpo system, but, which does not have more capability, has recently been installed (1995) at OC Transpo. While the model was designed to share the schedule files used in OC Transpo's AVLC system, so that simulation experiments are always done on the schedule currently used in the real system, it is currently functioning on a standalone basis (i.e., using fixed, older schedule data).

Functionally, the model has two kinds of ability: it provides a tool for the testing and evaluation of different service control strategies and policies, and it also serves as a "training simulator" for current and new controllers [6]. Validation experiments of the simulation model have been performed by Chen. The sensitivity analysis has shown that the model in general yields the expected behaviours. Therefore, we consider that the simulation model can generate relatively reasonable results in comparing and evaluating different control strategies and policies. However, it has been found that further calibrations of the model may be needed particularly for the afternoon peak period. As suggested by Chen, our further testing will be restricted to the morning peak period only, which has a 3-minute headway and meets our requirement of a high-frequency service [5].

In order to better use the model, Chen has also developed a prototype control module (knowledge-based system), which is capable of applying two ***headway holding policies*** (delay the departure of certain buses at certain control points along the route as the needs arise, in order to maintain a constant headway) according to the user's decision. After the user has chosen a control policy, the control module can control the simulation model automatically. The detailed descriptions and test results of these two policies (threshold policy and "message board" policy) can be found in [5]. Literature review has suggested that headway control strategy can play a key roll in improving the reliability for high-frequency bus service [3]. Chen's research has been focused on headway control strategy, and his research conclusions have also supported this suggestion.

The conclusions on the suitability of headway control strategy for high-frequency bus service and the development of the control module both provide important supports for this thesis research.

Section II.5 The Types of Bus Services

Bus service reliability is a function of the types of bus route. Different control strategies may apply according to the type of bus route [13]. Here we define a ***route*** as a collection of service patterns with common characteristics [21].

As part of our research, we have identified various types of bus route. The characteristics used for defining the types of bus route are different at different transit agencies. For example, at OC Transpo, the types of bus route are defined mainly based on the region that the route covers, the frequency of the service on the route, the service availability of the route, the fare applied to the route, etc. [21]]. In order to give a clearer description, the following indicators have been chosen to identify the types of bus routes:

▪***Service frequency*** of the route represents the level of the service, and is an important indicator in choosing a suitable control strategy. Usually, service frequency can by divided into three classes [11]:

□High-frequency service: headway shorter than 4 minutes (more than 15 buses per hour)

□Medium-frequency service: 4 to 10 minutes headway (or 6 to 15 buses per hour)

□Low-frequency service: more than 10 minutes headway (or less than 6 buses per hour)

☞The impact of service frequency of a given type of route on its performance reliability will be discussed briefly for each type of bus route.

▪***Service availability*** indicates the time period when the service of the route is available:

□All day service: full day service available for 7 days a week

□Weekday service: full day service only available on weekdays

□Peak-only service: service only available during the peak period of the weekdays

▪***Stop location and spacing***, which is highly dependent on the type of the route and the area being served. Usually, in heavily developed areas (i.e., downtown area), well-dispersed bus stops with short distances (less than 300 metres) in between are constructed to provide easy access and to reduce passenger congestion. However, on the transitway or freeway, stops are clustered at important transit points along the routes;

▪***Passenger usage*** depends on the area served by the routes and the time period of a day. For example, in heavily developed area and during the peak period more passengers will use the buses;

▪***Roadway facility*** used for the route is also a function of the types of bus route: for example, in order to achieve high operating speed for express routes, most parts of the express routes are chosen to be transitway, expressway or freeway;

▪***Average operating speed*** of different types of bus route can vary depending on the stop configuration, the length of the route, the available roadway facility, and the degree of traffic congestion along the routes;

▪***Fare*** may change for different types of route and for different time of the day;

▪***Service advantage***; and,

▪***Service disadvantage***.

Examples given in the braces { } to illustrate the various types of bus routes are taken from OC Transpo documentation [22].

II.5.1 Local Service Routes

The local service routes provide bus services in suburban communities with fixed operating routes and schedules, and do not service the downtown core directly. Indirect routing is usually used in order to improve service coverage. Another important characteristic of local routes is that they are usually designed to connect with one or more major transfer points, so as to be linked with other routes in the transit network. Examples of local routes from OC Transpo are: Route 125, 127, 133.

CHARACTERISTICS OF LOCAL SERVICE ROUTES:

- Service frequency: peak period: medium to low service frequency {as short as 7 minutes, usually 10 to 30 minutes}
  off-peak period: low service frequency {as long as 60 minutes, usually 20 to 30 minutes};
  ☞Given the above service frequencies, passengers are highly conscious of the schedules; performance and reliability are measured by schedule adherence.
- Service availability: all day service, service may be reduced during weekends and holidays;
- Stop location & Spacing: short distances between stops {usually less than 300 metres}; stops are well dispersed along the routes;
- Passenger usage: medium during peak periods, medium to low otherwise;
- Roadway facility: collection roadways and some arterial streets;
- Average operating speed: comparably low average speed resulting from short distance between stops and indirect routing, range [13,23] km/hour;
- Fare: no premium fare applied {off-peak: $1.60; peak hours: $2.10};
- Service advantage: high accessibility and area coverage, medium service frequency during peak periods;
- Service disadvantage: low operating speed and indirect routing result in long travel time, low service frequency during off-peak period, especially

at late evenings.

RELIABILITY OBJECTIVES

- Schedule adherence: try not to leave early at any stop;
- Connections with other routes at certain major transfer points: try not to arrive late at major transfer points.

SUITABLE STRATEGIES AND POSSIBLE POLICIES

- Schedule control strategy is very important;
- Interlining can be applied: a route either runs standalone or is interlined with other routes supplemented by peak-only trips. Deadheading may apply as we mentioned before (in section II.1).

II.5.2 Mainline Service Routes

Mainline service routes are also known as line haul routes. Characteristics of mainline service routes are cross-regional services, and direct service to the downtown core. Mainline routes service many transfer points so as to allow the users coming from the local routes to access to other sections of the city, and the downtown core in particular. At OC Transpo, mainline routes usually stop at more than one transitway stations to allow transfers with local service routes. Examples from OC Transpo are: Route 2, 7, 85, 8, 3.

CHARACTERISTICS OF MAINLINE SERVICE ROUTES:

▪Service frequency:	peak period: medium to high service frequency {as short as 5 minutes, usually 7 to 10 minutes}; off-peak period: medium to low service frequency {as long as 30 minutes, usually 15 to 20 minutes}; ☞ Given the above service frequencies, passengers may not be highly conscious of schedules during peak periods, thus headway control strategy may be applied. Schedule adherence is still important for long headway periods.
▪Service availability:	all day service; service may be reduced during weekends and holidays;
▪Stop location & Spacing:	stops are closely and regularly spaced {about 300 metres};
▪Passenger usage:	very heavy during peak periods, medium to heavy off-peak;

- Roadway facility: collection roadways and some arterial streets;
- Average operating speed: medium average speed combining low speed in downtown area and high speed on transitways, range from 20 to 30 km/hour;
- Fare: no premium fare applied {off-peak: $1.60; peak hours: $2.10};
- Service advantage: high accessibility at downtown area, direct service to downtown core, comparably high service frequency, and connectivity with several other routes;
- Service disadvantage: heavy passenger usage may cost overload, low service frequency during late evenings.

RELIABILITY OBJECTIVES

- Headway adherence: when headway is less than or equal to 10 minutes;
- Schedule adherence: when headway is longer than 10 minutes;
- Connection with other local and mainline routes at certain major transfer points: try not to arrive late at major transfer points.

SUITABLE STRATEGIES AND POSSIBLE POLICIES

- Schedule control strategy for low frequency service;
- Headway control strategy may be applied for medium frequency service.

II.5.3 Express Routes &Limited Stop Service Routes

Express service is a premium level service with long travel distance providing direct service between suburban area and the downtown core or some commercial centres. Express routes offer passengers a time saving over other non-express services and therefore a premium fare may be applied. Example from OC Transpo: Route 65.

Limited stop routes (non-express) provide services from suburban areas to the downtown core but can also be used to service non-downtown employment centres and schools. They do not offer a significant time saving over other services and thus, no premium fare applies. Example from OC Transpo: Route 47.

CHARACTERISTICS OF EXPRESS & LIMITED STOP SERVICE ROUTES:

- Service frequency: medium to low service frequency {usually less than 20 minutes};

☞Given the above service frequencies, and also because most of the passengers are regular users who are highly conscious of schedules (to be on time for work), schedule adherence is very important. Interlining used on these types of routes also makes it more difficult for headway control.

- Service availability: peak-only service;
- Stop location & Spacing: For express service routes stops are clustered in downtown core and in the suburban area (less than 300 metres in these two areas). Between these two areas, there are relatively few stops; For limited stop service routes: only few widely and irregularly spaced stops will be served along the route, stops are located at major transfer points or at major activity centres;
- Passenger usage: medium to high, the passenger flows are highly directional: in the morning peak, most of the passengers are heading to downtown core or a commercial centre, while in the afternoon peak, most of the passengers are heading to suburban area. Service is not provided in the opposite direction;
- Roadway facility: freeway, parkway, transitway, expressway or other high standard roadway;
- Average operating speed: For express service routes: the average speed is from medium to high {24 to 56 km/hour} due to the usage of high standard roadway facility and widely spaced stops between the suburban area and downtown area: a time saving is provided to the passengers;

  For limited stop service routes: medium {25 to 40 km/hour}, which is due to the widely and irregularly spaced stops. No significant time saving will be provided;
- Fare: For express service routes a premium fare is required for offering a time saving over long travel distance {off-peak: $1.60; peak hours: $2.70};

  For limited stop service routes no premium fare is applied {off-peak: $1.60; peak hours: $2.10};

- Service advantage: the much improved average travel speeds provide a shorter and more direct service between downtown core and some commercial centres to the suburban area;
- Service disadvantage: small area coverage of each route, relatively infrequent service {no service during off-peak period or weekends}. Low ridership also prevents the transit agency from expanding more express and limited stop routes outside of peak periods.

RELIABILITY OBJECTIVES

- Schedule adherence: try not to leave early at any stop;
- Connection with other routes at the major transfer points: try not to arrive late at major transfer points.

SUITABLE STRATEGIES AND POSSIBLE POLICIES

- Schedule control strategy is most suitable;
- Interlining can be used in producing operating efficiencies.

II.5.4 Communi Service Routes

Communi service routes are regularly operated in areas of cities that have greatest concentrations of residential complexes for elder and disabled, medical facilities, activity centres, and shopping centres. Buses used on this type of route can kneel and are equipped with a ramp so boarding is easier. The routes operate similarly to a circulator, connecting the major residential complexes with the primary destinations in the service area [26]. Examples from OC Transpo: Route 306, 307, 316.

CHARACTERISTICS OF COMMUNI- SERVICE ROUTES:

- Service frequency: low service frequency {usually every 60 minutes};
  ☞ Given above service frequencies, passengers are highly conscious of schedules: performance and reliability are measured by schedule adherence.
- Service availability: weekday service, not available on some national holidays;
- Stop location & Spacing: few stops with irregular distance in between;

- Passenger usage: medium;
- Roadway facility: collection roadways and some arterial streets;
- Average operating speed: low;
- Fare: no premium fare required {off-peak: $1.60; peak hours: $2.10}, service is free to those who have a valid Attendant Card;
- Service advantage: high accessibility and area coverage;
- Service disadvantage: low operating speed, low service frequency and indirect routing result in long travel time. Service frequency is very low.

RELIABILITY OBJECTIVES

- Schedule adherence: try not to leave early at any stop.

SUITABLE STRATEGIES AND POSSIBLE POLICIES

- Schedule control strategy;

II.5.5 Very High Frequency Mainline Service Routes

Very high frequency main line routes are main line routes characterized by very high service frequency during peak periods. Given the heavy passenger usage, at OC Transpo, articulated buses are mostly used to suit the heavy ridership. Example from OC Transpo: Route 95.

CHARACTERISTICS OF VERY HIGH FREQUENCY MAINLINE SERVICE ROUTES:

- Service frequency: very high service frequency during peak periods {3 minutes}, medium service frequency during off-peak period {4 to 10 minutes}, low service frequency in early mornings and late evenings {15 minutes};

  ☞ Given the above service frequencies, passengers may not be conscious of schedules during peak periods, thus headway control strategy should be applied. Schedule adherence is still important in early mornings and late evenings.
- Service availability: all day service; service may be reduced during weekends and holidays;
- Stop location & Spacing: stops are closely and regularly spaced {about 300 metres} in downtown area, and are more widely spaced along the

	transitway {0.5 to 4 kilometres};
▪Passenger usage:	very heavy during peak periods, medium to heavy otherwise;
▪Roadway facility:	transitway and high standard roadway and some arterial streets in downtown core;
▪Average operating speed:	medium to high average speed due to the heavy usage of high standard roadway facility {range from 35 to 45 km/hour};
▪Fare:	no premium fare required {off-peak: $1.60; peak hours: $2.10};
▪Service advantage:	high accessibility at downtown, direct service to downtown core, comparably high service frequency, and connectivity with several local service routes;
▪Service disadvantage:	heavy passenger usage may cost overload, low service frequency during late evenings.

RELIABILITY OBJECTIVES

▪Headway adherence: when headway is less than or equal to 10 minutes;

▪Schedule adherence: when headway is longer than 10 minutes;

▪Connection with other local and mainline routes at the major transfer point: try not to arrive late at major transfer points.

SUITABLE STRATEGIES AND POSSIBLE POLICIES

▪Headway control strategy is most suitable for high frequency service;

▪Schedule control strategy for low frequency service.

☞ FOR ALL TYPES OF BUS ROUTES MENTIONED ABOVE:

▪The use of schedule control or headway control strategy depends on the planned headway. For example, on Route 95, during early morning and late evening, schedule control actions should be applied while in other periods of the day when headway is shorter than 15 minutes, headway control strategy is most suitable. Therefore, from the service control point of view, service frequency is the most important characteristic in choosing the suitable control strategy;

▪Service restoration/ recovery techniques, passenger loading and alighting control strategy and extraboard management may apply if needed.

III. Headway Control & Flexible Scheduling

From our previous discussions and summaries about bus control strategies, we have had an understanding that different situations need different control strategies. Headway control strategy has been shown [1][5] to be effective to improve service reliability on high frequency services; however the implementation of headway control policies might affect the schedule adherence because the control actions aimed at keeping the service regularity may cause schedule deviations. As the headway gets longer, schedule adherence becomes more important since the passengers tend to evaluate the service mostly based on the service punctuality. Therefore, headway control strategy might not seem suitable.

How customers perceive service reliability is dependent on headway. This leads to the problem of determining what is the maximum planned headway such that headway control is more appropriate than schedule control or stated differently, what is the smallest service frequency such that most passengers will start checking the bus schedule before heading to the bus stops? To answer this, we conducted a small survey on the users of OC Transpo.

Section III. 1 A Customer Survey

III.1.1 Purpose of the Customer Survey

As we mentioned earlier, our tests will be based on Route 95, which is the backbone of the transit network operated by OC Transpo. Due to its importance in the transit network, OC Transpo always try to improve the services on Route 95. In particular, since the summer of 1994, OC Transpo has increased the frequency of Route 95 in the early evening. This improvement in service was thus introduced after the development of both the simulation model and the control module. The following is a table comparing the changes of headway on Route 95 on weekdays before September 1994 and now:

Table III.1.1. Comparison of headway of Route 95 before and after Summer 1994

(The numbers are headway in minutes)

Time period of the day	BEFORE	NOW
Early morning (4:00--6:30 AM)	15	15
AM peak (6:00--8:30 AM)	3-4	3 - 4
AM off-peak(8:30 AM--3:00 PM)	5	5
PM peak (3:00--5:30 PM)	3 - 4	3 - 4
PM off-peak(5:30--7:30 PM)	5	5
early evening(7:30--10:30 PM)	15	10
Late night (10:30 PM-1:00 AM)	15	15

From the above table, we notice that a new service with a 10-minute headway is now available on Route 95 from 7:30 PM to 10:30 PM. This change will have some impact on the simulation model and the control system. With the flexibility of the simulation model, no changes need to be made to the system code given this new service: however it will be necessary to update some relevant data files (including the trip file, the block file and some regulation files), which can be retrieved from the actual schedule data files from OC Transpo AVLC system. The control module was designed to control the movement of the buses in the simulation model using headway control strategy if the headway is 3 or 5 minutes, and the headway control would switch to schedule control when the headway was greater or equal to 15 minutes. With this new 10-minute headway, we need to make some adjustment to the control system accordingly by answering this question: **Which control strategy (headway control or schedule control) should be used with a 10-minute headway?**

In order to answer this question, it would be useful to do a survey to get the opinion of passengers: our goal is to do things right, that is, to use the most effective on-line control policies given the control strategy (ie. either headway or schedule control strategy). However, it is equally important to do the right thing, that is, given the service offered, to choose the most suitable control strategy to provide better service to the users so that they will perceive the service as well as the methods controlling the service to be appropriate and good. Therefore, we decided to do a customer survey on passengers at different bus stops at different times of the day, and to analyse the results of the survey based on their answers and comments. We believe that the feedback from the users should allow us to consider a reasonable alternative to improve service control in our case.

The main purpose of this survey is to identify the maximum headway (h_{max}) such that the headway control strategy should still be more appropriate than the schedule control strategy to control the buses. Given h_{max}, we will be able to answer the question above, regarding the ***planned headway (hp)*** (also known as the scheduled headway, which is defined as the predetermined headway over a period of the day and which reflects the level of service provided to the users) of 10 minutes. The control strategy to implement will depend on both the planned headway and h_{max}, as follows:

- If h_{max} > hp: implement headway control strategy;
- If h_{max} <= hp: implement schedule control strategy.

As we discussed earlier, the information provided through "560" system is basically schedule information which cannot keep up with on-line schedule changes and the changing conditions in the real transit network immediately. This lack of quick adapting to the real system will have impacts on the service control as well as on the performance evaluation from the passengers. This can be clarified as follows: if the buses are all running exactly according to the schedules, the "560" will provide perfect information to the public. But as buses are not necessarily running on schedule, the unmatched information may mislead the passengers' arrival behaviours: for example, if a bus is early, the unchanged schedule information provided to the passengers may make them miss the bus, and thus will have a negative impact on the perceived service reliability. This is also true when a control policy is applied, because the control action may push buses off their schedules to gain a better overall performance (i.e., a better service regularity). Previous experiments show that buses tend to run late compared to the planned schedule [5] when headway control strategies are used. The effectiveness of this kind of control actions may be affected by the "560" system, if passengers still base their arrival to the stops on information from the "560" system or from the public bus schedules. Passengers may be tempted to evaluate service performance based on schedule adherence while drivers will also tend to auto-regulate themselves based on available timetables. However, since regularity is the main issue when the planned headway is small, the importance of scheduled departure times should be de-emphasized. Therefore, we propose some changes in the information which should be made available to the public when the service frequency is high and the headway adherence is more important than the schedule adherence. Given the reasonable assumption that for a short headway, passengers do not refer to the timetable before heading to their stops, it is not useful to provide users with detailed schedules. It is preferable instead to simply mention the service frequency: for example, "bus service is every three to four minutes" would be a more appropriate information than listing the exact departure time at certain stops. Given this new information, passengers would then evaluate the reliability of the service based on the service regularity rather than based on schedule adherence. Hence, by changing this public schedule information, a better match between the passenger's expectation and the headway control strategy will be achieved. We thus propose that the passengers be given the planned headway instead of a fixed timetable during the period when headway control strategy is active.

This change will involve all the components of the public schedule information systems, including the printed schedules, the "560" tele-information system and schedprints (stop-specific public timetables which are physically located at bus stops in specially designed route-director boxes). After the proposed change, the information from the public schedule information systems will be something like this: "The service is every 5 minutes". The passengers will not know the exact scheduled departure time of the bus at any stop. In reality, this change has already been partly implemented on the schedule of Route 95 (see appendix VII.2) during the AM and the PM peak periods.

Our major concern is how will the passengers react to this change? What is the largest headway such that they will accept not having detailed schedule information before heading to their stops? Given this change, the passengers' average waiting time could be as long as the planned headway, but it is hoped that by better headway control, it will not be longer than the planned headway and that the expected waiting time will approximately be half the planned headway. Given short headway and lack of information regarding the detailed schedules, passengers will arrive at the stop randomly (i.e., as in a Poison arrival process), and ***formula II.2.1*** can be used to calculate the passengers' average waiting time (AWT).

To use this, from the formula, we notice that as S.D.(h) decreases (which is the goal of the headway control strategy), the AWT also decreases. Given a planned headway hp, if we can minimize the variance of the actual headway to be zero, the expected waiting time of the passenger (whose arriving behaviour at the stop obeys a Poison process) will be minimized to be 0.5 hp . This will be considered as the ideal service we are seeking by using the headway control strategy. Decrease of the AWT should be one of the performance measures used to evaluate headway control policies.

Another aspect of ***formula II.2.1*** is that as long as the headway is short enough to keep the Poison hypothesis valid, then by providing good headway control, passengers can expect their average waiting time to be nearly half of the planned headway even if they do not know the exact schedule and just head to the stop randomly.

As the headway gets longer, passengers will tend to head to their stops just a few minutes prior to the scheduled departure time in case the bus runs early to minimize their waiting time. The situation gets more complex: the longer the headway, the more passengers will check the schedule before heading to their stops, and the more of them will associate "reliable" service with the schedule adherence. Obviously, the bus control strategy should fit the passengers' expectation of good service: if the service frequency is so long that most of the passengers expect the bus to come according to the scheduled time, headway control may not be suitable. We already discussed that we can affect part of the passengers' behaviours and service expectations by choosing what information should be made available to the public. For long headway service, detailed schedules should be made available while for high frequency service, it may be better to simply state the service frequency (headway). To find the smallest headway at which point detailed schedule information would be required from most passengers is also one of the motivations of our survey.

In the following pages, we will discuss how we formulated the questionnaire for the survey and analyse the results from the survey.

III.1.2 Design of the Survey

The first and most important question we would like to ask the passengers is "What is the maximum planned headway in your opinion such that the headway control strategy would still be reasonable to be used to control the buses?". However, given that most of the passengers are not familiar with technical terms such as "headway", "headway control strategy", they may not be able to answer this question. A short questionnaire must be designed to obtain the useful and correct information we need. In order to meet the goal of our customer survey, five questions were formulated. We tried to keep them as short and as clear as possible. We decided to ask a few short questions, to which the passenger can provide a short easy answer, so that the survey could be performed quickly. Among the five questions (included in Appendix VII.3, VII.4 and VII.5), the 4th and 5th are the most important ones.

Question No. 1, 2 and 3 are easy general questions of a personal nature used to make respondents feel comfortable quickly. These questions are also used to verify the consistency of the respondents' answers. For example, suppose a passenger answered "10 minutes", "10 minutes", and "3 minutes" to question No. 2, 3, and 5, hence he usually heads to the bus stop 3 minutes before the schedule departure time, but he arrived to his stop about 20 minutes ahead of the schedule this time. His behaviour (given his answers to question No. 2 and 3) would contradict his answer to question No. 5, and we would try to understand why by asking him more questions. Some other useful information might also be found. We also keep a record of which bus the passenger is waiting for further usage, but this information is less important to us, since the critical questions are independent of the bus route.

Question No.5 is also designed to identify other possible contradictions as explained below: suppose the respondent answers "5 minutes" to question 5, which implies that he wishes to arrive 5 minutes early if he knows the exact schedule. Under good conditions, that is, assuming the buses are usually on time (sometime a little early, sometime a little late), his average waiting time would probably be 5 minutes, which suggests that he might accept (or tolerate) an expected waiting time of 5 minutes. Given this acceptable expected waiting time, it would seem reasonable to assume this passenger would not need to know the exact schedule if the headway is 10 minutes, since under good headway control, that is, buses being regular, his expected waiting time would also be about 5 minutes. Hence, his answer to question 5 should agree with an answer of 10 minutes to question 4.

In designing question No.4, we tried to help the passengers have a better understanding of headway. We first decided to present the existing planned headway (less than or equal to 30 minutes) which are currently used at OC Transpo to the passengers and let them choose. Question No.4 was originally formulated as follows: "Assuming the time between two successive buses is 3 minutes, would you like to know the exact scheduled departure time of the buses?". We would then go on increasing the value of the headway in this question until the passenger would answer "yes". But we suspected that the order in which we presented the headway (from small to large) may create a bias so we formulated question No. 4 in another version. In this second version, we decided to start with a large headway (30 minutes), and then move down to smaller ones, stopping when the passenger said "no". To test whether the bias exists, we performed twenty surveys in each version of question No.4. The two versions of question No.4 are attached in appendix VII.3 and VII.4. If there existed a bias, we would try to find out the reasons and try to overcome the bias so that we could get the correct information. If there did not exist any difference in the statistical characteristics of the results of question 4 in the two sets of surveys, we would be justified to carry on to do more surveys using one of the two versions of question 4.

In order to make the answers as general as possible, the survey has been done in different periods of the day and in different places including campus, downtown shopping centre, urban shopping centre, local stops, etc.

For clear explanations, in the following discussions we will define:

Set 1: the passenger group who were asked question No. 4 in an increasing order of headway;
Set 2: the passenger group who were asked question No. 4 in a decreasing order of headway.

Results for these 40 surveys are as follows:

Table III.1.2. Results Based on Original Survey Data

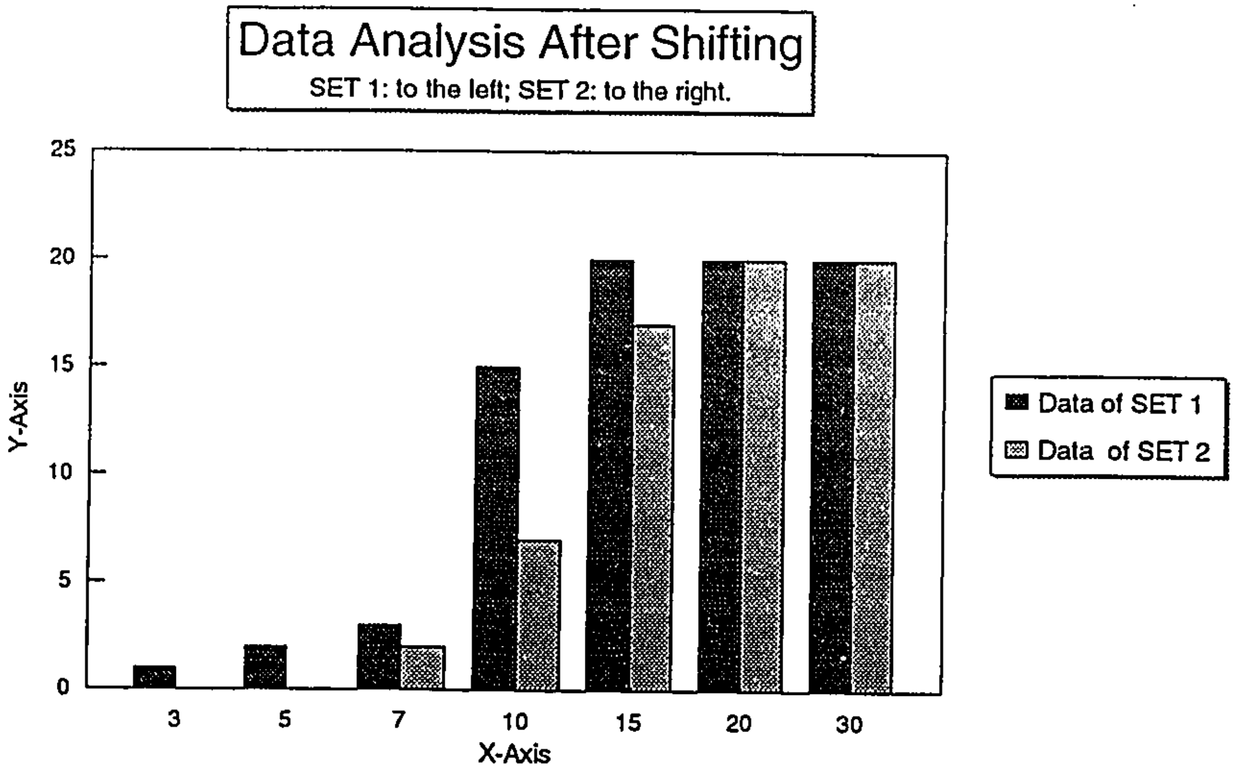
Chosen Headways (in minutes)	Number of passengers that would need the detailed schedules for this headway (answers of *set 1*)	Number of passengers that would need the detailed schedules for this headway (answers of *set 2*)
3	1	0
5	1	0
7	1	2
10	12	5
15	5	10
20	0	3
30	0	0

In analysing these results, we noted some ambiguity in the answers provided for question No.4. To illustrate this, suppose a respondent in ***set 1*** said "yes" to 10 minutes headway but "no" to 7 minutes headway, this may mean that the respondent might need schedule information for headway greater than 7 minutes but smaller than 10 minutes. Given the way the question No. 4 was asked, we can only conclude that the true answer of the respondent lies in the time interval (7, 10] minutes. The data obtained from question No.4 in ***set 1*** in headway might need to be shifted to the left side to present the real information. Doing the same analysis of the data obtained form ***set 2***, we came to the conclusion that the information might need to be shifted to the right. Therefore, another approach of reporting the data has been used as shown in the table below:

Table III.1.3. Data Analysis After Shifting Original Data to the Proper Time Interval

Chosen Headways (In minutes)	Total number of passengers who would require detailed schedule information if the headway is less than or equal to the following (data of *set 1*)	Total number of passengers who would require detailed schedule information if the headway is less than or equal to the following (data of *set 2*)
3	1	0
5	2	0
7	3	2
10	15	7
15	20	17
20	20	20
30	20	20

The following figure presents these results on a bar-chart:



x-axis: headway in minutes
y-axis: number of passenger requiring schedule information if the headway is less than the following

Figure III.1.1 Bar-chart of survey data of *set 1* and *set 2*

In order to find out whether there exists a bias, we did the following tests:

Let: u_1 = the mean of the answers for question No.4 of ***set 1***;

u_2 = the mean of the answers for question No.4 of ***set 2***.

Null Hypotheses: $H_0 : u_1 = u_2$;

Alternative Hypotheses: $H_1 : u_1 \neq u_2$.

Use Minitab to do the following tests with $\alpha = 0.05$:

```
Twosample T for set 1 vs set 2
             N     Mean   StDev  SE Mean
     set 1   20    10.50   3.27    0.73
     set 2   20    13.70   3.93    0.88        (N is the number of observations)
95% C.I. for mu set 1 - mu set 2: ( -5.52, -0.88)

T-Test mu set 1 = mu set 2 (vs not =): T= -2.80  P=0.0082  DF= 36
```

Since ***P-value*** is smaller than 0.05, we reject the null hypotheses. So we have at least 99% confidence that the mean of the answers for the two sets of the survey are different-the mean of ***set 2*** is most likely greater than the mean of ***set 1***. Therefore, we concluded there did exist a bias in the two sets of information in question No.4. Our explanations for this bias are as follows:

①The order of the headway presented to the passengers might have affected the way they answered this question. With the increasing order in ***set 1***, 10 minutes seem to be large compared to 3 minutes, while with the decreasing order in ***set 2***, 10 minutes might seem small compared to 30 minutes which was asked first. This impression might have made the passengers tend to give their answers closer to the number we first asked. The results of the survey supported this tendency.

②There existed some uncertainty in question No. 4 because it was using current headway used at OC Transpo, which left gaps in between. This made the MEAN and STANDARD DEVIATION less meaningful than those that could be developed had we asked the passengers to give a specific value as opposed to this multiple choice.

We still obtained much useful information from these 40 surveys:

- For the 40 answers, we had only one answer of 3 minutes but no 30 minutes, which would help us in the re-design of question No.4. We also had an idea that the correct answer should be between 7 and 15 minutes, which confirmed the importance of this survey relative to our simulation research project and gave us the motivation to continue to work on it;
- The other four questions in each set were useful so that we can use them for future analysis and include them to the results of the updated survey. Some other comments were also helpful. It

was also an interesting experience to talk with passengers.

To overcome the bias in questions No.4, we re-designed the survey in the following ways: First we combined the two questions in No.4 in ONE to overcome the bias. Second, we made sure that the passengers could answer the question by giving a precise number to overcome the ambiguity of time intervals.

The updated version of question No. 4 contained three sub-questions (4a, 4b and 4c) as follows:

4a: Assuming the time between two successive buses is 30 minutes, would you like to know the exact scheduled departure time of the bus?

4b: How about 3 minutes?

4c: What is the largest time interval for which you would not need to know the scheduled departure time before heading to the bus stop?

Instead of suggesting the passenger headway in orders, we decided to ask two sub-questions 4a and 4b, and then let the passenger make his own decision in answering sub-question 4c. The organization of these three sub-questions in question No. 4 followed the following rules:

①Given the previous survey, we expected that the passengers would like to know the exact scheduled departure time when the time between two successive buses was 30 minutes. Also by common sense, we could tell that nobody would like to wait half an hour for his bus even when he was not in a hurry. Therefore we could expect the passenger to answer "YES" to sub-question 4a. If the passenger answers "NO", we would skip 4b, and ask sub-question 4c. The exact number in minutes would be recorded;

②If the passenger answered "YES" to 4a as we expected, 4b would then be asked. We were also confident from previous results that over 95 percent of the passengers would not require the exact schedule if buses came every three minutes. If the passenger said he did want to know the exact scheduled departure time of his bus, 4c would be asked. The exact number in minutes would be recorded;

③We decided to ask 4a and 4b before 4c to give the passengers a better understanding of what we were really asking for in this question. If they answered "YES" to 30 minutes and "NO" to 3 minutes headway, then, when 4c was asked, they would have an idea that the answer should be between 3 and 30 minutes;

④The way that sub-question 4c was asked left the passenger free will to choose any number without being tied to fixed values. The answers we got were exact numbers: it makes it easier to analyse the mean and standard deviation.

The other four questions were kept the same as they were in the original questionnaire.

Ninety passengers were surveyed using the new questionnaire (also attached in appendix VII.5) in January, 1995. The survey was also done at different stops in different areas of Ottawa, and in different time periods of the day. Usually it took less than 2 minutes to do one survey, unless more explanations needed to be given or more comments were given by the passengers. From the survey, we found that most of the passengers understood that buses would not always be as reliable as taking a taxi or driving their own car because of various sources of variability which were not under their own control with this mode of transportation, and most of them were quite happy about the current bus service. Most of them were quite patient and cooperative. Therefore we were not very surprised with the results of this survey (the average maximum headway for which passengers would not need schedule information came out to be 13.3 minutes). On the other hand, we found there still existed some problems in bus services, such as bus running early or late, missing trips, overloading during peak hours and bus breakdowns, which also need to be addressed.

III.1.3 Analysis of the Customer Survey

As far as this thesis is concerned, we will do the following data analysis of the survey to find out what is the maximum headway (h_{max})such that the headway control strategy should still be used to control the bus service:

①Statistical analysis of the answers in question No.4, including the mean, the standard deviation, and the distribution to find the statistical answer to our question.

Using Minitab software, it is easy to find the statistical values of h_{max} :

```
Descriptive Statistics
Variable    N       Mean      Median    TrMean    StDev    SEMean
hmax        90      13.300    15.000    13.200    3.884    0.409
Variable    Min     Max       Q1        Q3
hmax        7.000   25.000    10.000    15.000
```

One possible way of obtaining h_{max} is to take the average of the values obtained from the passengers in the survey:

Mean of h_{max} = 13.3 minutes

Based on this calculation, for the new 10-minute service introduced by OC Transpo, headway control should be used. The low variability in the passengers response should be noted, as demonstrated by the very narrow confidence intervals around h_{max}.

95% Confidence Intervals of h_{max}:**(12.486, 14.114) minutes**

This is a bar-chart representing the data in question No.4 of the final survey:

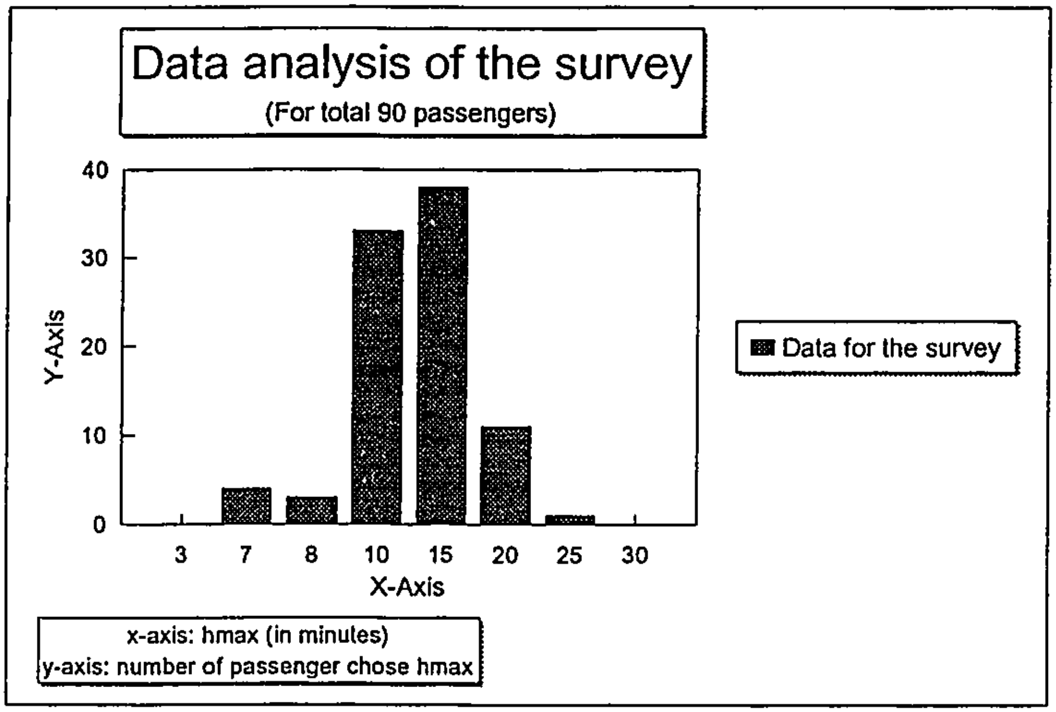


Figure III.1.3 Bar-chart for data of question No.4 in the final survey

We can see that although the data range from 7 to 25 minutes, statistically we can have 95 percent confidence that the value will be in the interval of (12.486, 14.114) minutes. It should be noted that 56% (50 out of 90) of the answers are greater than 14.114 minutes. Therefore, a more useful way to organize the data is to find out the percentage of passengers who would not require schedule information if the planned headway was 10 minutes: from the survey results, this proportion is 92.2%. If we include the results of the first forty passengers surveyed, this proportion is still very high at 90.8%. With this result, we can recommend the use of headway control when service frequency is 10 minutes.

②Statistical analysis of the answers in question No.5, which represent how long (t_5 in minutes) before the scheduled departure of the bus at the stop will passengers head to the stops.

From our previous analysis, we propose to use headway control if the planned headway is 10 minutes. If this is implemented, and suppose a "reliable" service according to headway adherence is provided, then, if the exact schedule information are not available to the bus users and they just arrive to the stops randomly, we know their Average Waiting Time (AWT) will be about half of the headway, say about 5 minutes. We would like to compare this to the answers from question No.5.

We do the same data analysis of t_5 (based on the total 130 surveys) as we have done for h_{max}:

```
Descriptive Statistics
Variable    N     N*   Mean    Median   TrMean   StDev   SEMean
   t5      129    1    5.287   5.000    5.214    1.966   0.173
Variable   Min         Max          Q1            Q3
   t5      2.000       10.000       4.000         6.000
95% Confidence Intervals  t5:  (4.944,  5.629) minutes
```

Therefore, as long as a reliable service can be provided, using headway control strategy on 10-minute planned headway would yield an expected waiting time to the passengers which is in the same order as the expected waiting time derived from question No. 5. Hence, the answers to these two questions seem consistent.

③Use other information by combining question No.2, No.3 and No.5 together and to see if there is any adjustment needed to be made to the answer we get for question No. 4.

Although on average, the passengers head to their stops 5.3 minutes before the scheduled departure time, it seems most of them would wait more than that (known by adding the answers in question No.2 and No.3 together). Their explanations for this fact were various, including not easy to get access to the schedule, just missed one bus, etc., but most of them show some understanding of the service frequency (headway) and tended to head to their stops without looking at the schedule when headway was short.

④Find out the reasonable answer to our main question.

Out of the 130 passengers, only 12 answered they would like to know the scheduled departure time of the bus when the service frequency is less than 10 minutes, which represents about 9.2% of the population. These passengers would still evaluate 10-minute service based on schedule adherence and may not be satisfied if buses start to deviate from the schedules (due to headway control). However, this proportion seems small. Furthermore, notice that among these 12 passengers, only 4 of them usually arrive at the stop less than 5 minutes before the scheduled departure time of the bus, which suggests the others may tolerate 10 minutes headway control if they understand that with a good headway control service, their expected waiting time should be just about 5 minutes. Even if the 10 minutes headway control may not satisfy every passenger, we believe most of the passengers will benefit from this strategy. We believe that headway control strategy should be more suitable if the planned headway is less than or equal to 10 minutes.

As far as Route 95 is concerned, 10-minute service is provide in early evening (7:30 PM to 10:30 PM), during which period the headway of most other routes are greater than or equal to 30 minutes. An argument against headway control during this time period is that the schedule adherence might be very important regarding the connection capability of Route 95 with other (local) routes in the transit network.

The surveys were done during the period from December 1994 to January 1995. Since the weather was very cold, we are confident about the validity usefulness of the results, because the "longest headway" that the passengers are willing to accept in December and January in Ottawa should be shorter than the average headway they would be willing to accept any other time of the year. In other words, if passengers accept to wait 10 minutes in December and January in Ottawa, they should be willing to wait at least 10 minutes on average during the rest of the year under milder weather conditions.

The following three sections will focus on a new headway control policy which we refer to as flexible scheduling. The importance of headway control for high frequency service and how the flexible scheduling is developed will be discussed in the first section. Detailed descriptions of flexible scheduling and how we are going to implement this policy will be given in the second section. In the third section of this chapter, we will give a simple theoretical analysis demonstrating the potential effectiveness of the flexible scheduling policy.

Section III.2 Building Flexibility in the System

Previous experience and research in improving bus service have shown that when the headway is reasonably short, it is desirable to implement headway control strategy to improve the service reliability [3][5]. Our customer survey also suggests that for short headway service, passengers tend not to rely on schedules before heading to their stops. In the previous chapter, we have already made a summary on the headway control strategy and those control policies which support headway control strategy. Compared with schedule control policies, few research has been done in evaluating headway control policies; two headway control holding policies, namely the threshold and the message board policies have been shown to be effective given short headway service [5].

The most important characteristic of headway control strategy is headway adherence. Keeping actual headway equal to the planned headway as opposed to adhering to schedule is the critical issue in service control. Previous research has already shown that when a bus is running early according to the headway, we can "hold" that bus to provide a better overall service [5]. The next question we would naturally like to ask is what to do if the bus is running late? Of course, there exist some options include speeding up the bus, or, skipping some stops, or, deadheading (skip part of the trip) to the terminal. Another alternative to address this problem may be try to prevent the delay in departure from occurring by having some extra resources (to have one or more extra buses waiting at terminals or some control points to fill in the late trips) or to build some slack times into the schedule, for example, plan a longer recovery time than the minimum recovery time (which is none) at the end of each trip. By increasing the system capacity through added resources or slack, the system will be able to adapt to changing conditions more easily. We believe that this excess capacity combined with an effective headway control holding policy for example, would result in improved service.

We define the ***flexibility*** in a system as its ability to adapt to changing conditions. The objective of having some extra resources or slack is to help achieve constant inter-departure time between trips during high-frequency service periods. By increasing the system capacity, we increase its flexibility.

III.2.1 Use of One or More Extras to Increase System Capacity

We claim that the effectiveness of holding policies can be improved by increasing system capacity. One way of doing this is to provide one or more extra buses dedicated to a given route to fill in for late buses in order to keep the actual headway as close as possible to the planned headway. Thus the system would be flexible in two ways: first, the extra drivers provide slack so that service may be maintained even if a driver finishes his trip late. Second, the work assignment of each driver would no longer be fixed, but flexible, so that drivers could be asked to change roles and possibly become an extra, as described below.

The implementation of this method follows these steps:

①Given the planned headway during the period of interest, the minimum number of buses would be allocated on the route, such that the layover time at the end of each trip meets the minimum required by the labour agreement rules, and the service recovery time is zero. For Route 95 at OC Transpo, current practice is to use 4 minutes as the minimum layover time for each trip. The formula used to compute the minimum number of buses needed is given below:

Formula III.2.1

$$N=\left\lceil \frac{Ttrip(1)+Ttrip(2)+2\times(Tlayover+Trecovery)}{hp} \right\rceil$$

Where:

N = the minimum number of buses needed to cover a route given a planned headway hp;

$\lceil x \rceil$ gives the smallest integer that is greater or equal to x;

T*trip* (1) = the average trip travel time of one direction (e.g., eastbound of Route 95);

T*trip* (2) = the average trip travel time of the other direction (e.g., westbound of Route 95);

T*trip* (1) and T*trip* (2) may/may not be the same;

T*layover* = the minimum layover time assigned to the trips for a given route;

T*recovery* = the service recovery time, here T*recovery* = 0;

hp = the planned headway.

Mainline routes, such as Route 95 at OC Transpo, usually are not affected by interlining. Therefore, the number of buses to cover a given route for a period of time with a given planned headway will be an integer. Rounding up insures that N is integer and large enough to provide the planned service given by hp.

②At each terminal, an optimized number of extra buses dedicated to the route will be waiting to fill in if need arises. We want to keep as few extras as possible to save on costs;

③A timer or a clock at each terminal is proposed to provide the current planned headway (h*p*)and the time elapsed after the departure of the previous bus (T*p*) on the route: for example, at each terminal the timer will tell the drivers this information: "**Route 95** ⌚☞ The current planned service frequency is every **3** minutes, and the last bus left **2** minutes and **10** seconds ago.";

④The extra driver waiting at a terminal observes the timer and the arrival of the bus which is scheduled to take on the following trip;

⑤If the time left before the departure of the next bus is approaching zero (Tp is approaching hp), and the bus scheduled to take on the next trip is still not ready to do so, the extra will advise the controller who will decide whether the extra bus should take on the next trip or not;

⑥By appropriately locating detectors, the controller will be able to determine the position of the coming bus if it has not arrived, as well as the layover time left for the late driver. Therefore, the controller will be able to decide whether the extra driver should fill in the trip or not. If an extra is available at that terminal, the extra should fill in to keep the dispatching headway constant and allow the other bus to have appropriate layover time;

The extra bus driver may need to fill in the next trip when the following situations occur:

☹. The bus scheduled to do the following trip has not arrived yet;

☹. The bus scheduled to take the following trip has arrived, but is still boarding/alighting passengers or still in its layover period.

⑦If a "fill in" answer is given, the extra driver will leave the extra position to fill in the following trip and become a regular driver;

⑧Given the extra driver took over the trip of the late driver, the late driver would then become an extra.

Based on the above algorithm, the driver's behaviour will mostly depend on the current planned headway of a given route on which he is operating. With this algorithm, in order to introduce certain degree of flexibility (depending on how many extra buses are available) into the system to keep the headway more stationary, at least one extra driver will be needed and dedicated to that route for the purpose of increasing system capacity. Given the additional resources in the system, the service should improve, for a given planned headway; however, we cannot ignore the fact that extra costs will occur accordingly, which is one of the major drawbacks of this method. Of course, if in the current system, more buses are used than the minimum number needed to cover the planned service level, and if it can be shown that the proposed method will provide at least the same level of service with less resource, some resources may be saved in the real system.

Such a policy may also be difficult to implement, both in the real system and in the simulation model. This is because requiring late buses to become extra can create problems at the end of the shifts (of the drivers or of the blocks). More specifically, the sequence of buses on the route would be altered. In the best scenario, drivers would complete their shift late, possibly increasing the overtime costs. In the worst scenario, the new sequence of buses could be such that many consecutive buses would be scheduled to leave the system (for example, after the peak period), leaving a large gap between buses that remain in service during the following off-peak period. This is illustrated in the following figure:

TA ⏭ → → ❶ → ❷→❸→❹→❺→❻→⑦→⑧→⑨ →❿ → → ⏮ TB

Figure III.2.1 Sequence of buses on a certain route and the symbols used for our discussions

Where:

❶: the dark bubble represents a bus scheduled to stay in the system after the peak period, and the number inside the circle represent its position in the bus sequence;

①: the light bubble represents a bus scheduled to leave the system after the peak period;

⏭ and ⏮: represent the terminals of the route, TA = terminal A in one direction, TB = terminal B in another direction;

→: the arrow represents the direction of the movement of buses on the given route.

With the above situation at the end of the peak period, drivers for bus ⑦, ⑧ and ⑨ in the bus sequence are scheduled to finish their working shifts shortly before or after the peak period, and it is either not reasonable or costly to assign them another trip. But we can see that if they all leave the system according to their scheduled working shifts, a problem will be created: a long time gap (about 4 times the planned headway) will be left between bus ❻ and bus ❿ in the sequence, which will remain in the system after the peak period. Thus, the service reliability will be reduced.

In order to keep the sequence of buses constant and to avoid such problems, it would be preferable to add this extra bus into the system and thus to build slack into the schedule.

III.2.2 Build slack into the schedules

As we mentioned earlier, slack built in the schedule will bring flexibility into the system. The time between two successive trips in the schedule is made up of two components: the travel time for the trips and the service recovery time given that the minimum layover time is always respected.

We know that the actual the trip travel time will always vary from the scheduled travel time due to many reasons, including the route conditions, the traffic conditions, the passengers' arrival rate, the weather conditions, and so on. It is important to realize that adding the slack in the trip travel time may cause service to deteriorate, because different drivers may handle this slack differently. For example, some drivers may like to drive fast to the terminal to have more layover time, while some others may prefer to drive slowly. This scheduled longer trip travel time will most likely end up with a higher variance in the actual headway. Therefore, we propose to use a reasonably short trip travel time as T*trip* in the schedule which will allow most of the drivers to finish the trip "on time" for a given period of the day (in the morning and in the afternoon, in the peak and off-peak, and in one direction and the other direction, the scheduled trip travel time may not be the same). At OC Transpo, a bus is considered "on time" if, according to the schedule, it is not early or no more than 3 minutes late. Therefore, we suggest setting T*trip* to be 3 minutes less than the average trip travel time. By using this reasonably short trip travel time, we will build the slack time into the service recovery time and keep the minimum layover period (T*layover=4* minutes in our case).

In building the slack of the system into the scheduled service recovery time, the system will have some excess capacity. For example, for Route 95, assume a 4-minute layover time plus a 4-minute service recovery time is assigned at the end of each trip: if all goes as scheduled, the drivers would expect an 8 minutes break time after each trip. However, the scheduled service recovery time allows for up to 4 minutes of flexibility, which can be used if the driver arrives late (by as much as 4 minutes) or if the driver needs to leave early (also by as much as 4 minutes assuming he arrives on time) which may occur if the preceding bus cannot take on its trip, for example.

Of course, building such slack (or scheduled service recovery time) may require operating more buses than the minimum number given by ***formula III.2.1*** over the same time period. Some modifications in the trip travel time (T*trip* (1) and T*trip* (2) in ***formula III.2.1***) need to be made in this case: T*trip* (1) and T*trip* (2) in this case are the reasonably short trip travel time that will allow most of the drivers to finish their trips "on time".

Hence, we propose that the slack in the system will provide a better service, in the sense that this excess capacity will allow the system to maintain the planned service level more easily.

We always round up when calculating the minimum number of buses needed for the current planned headway. This is because given that we require an integer number of buses, if we round down, the resulting number of buses would be insufficient to cover the planned service level. By rounding up in ***formula III.2.1***, we may build some slack into the system. We can see that with a longer *Tlayover*, more resources may be needed. Therefore, more cost may apply, which is a major drawback of this method.

Section III.3 Headway Control Using Flexible Scheduling

Our goal is for the system to provide the best service based on the planned headway, given the available resources. Therefore, given the previous discussion, we propose that using a holding policy in a system with some excess capacities may be a useful method.

With all the difficulties in implementation and the drawbacks of increasing the operating costs of the two methods we discussed in section III.2, the idea of flexible scheduling was originally discussed as follows:

Drivers are told that for a given time period of the day, they are to drive on a given route, for example on Route 95, but the exact departure time for each trip from the terminals is left open (flexible, not fixed) as well as the exact time and place at which they start/end their shifts. This follows from applying holding policies which tend to have buses start later than scheduled (while keeping the headway at terminals more constant). Adding excess capacity in the form of slack in the schedule or of extra should increase the likelihood of maintaining a constant headway at the terminals since all buses have more time between trips to allow for recovering the possible delays in the preceding trip.

In the following pages, we are going to develop a method that can adapt to the available resources as well as to the changes in the system so as to try to keep the service level as close to the planned headway as possible. We refer to this method as flexible scheduling.

III.3.1 Definition and Description

Flexible scheduling is a dispatching rule used on high-frequency service which determines the trip departure times dynamically at terminals and possibly other control points based on the actual achievable headway between successive buses. The ***achievable headway*** is the shortest headway which is feasible given the number of buses available to cover a given route. Flexible scheduling is an improved "holding" policy: given the planned service level defined by the planned headway (h_p), over a given period of the day, the objective of flexible scheduling is to dispatch a bus h_p minutes after the preceding departure so as to maintain regularity at the terminals and control points: this is similar to a holding policy. However, flexible scheduling is more than a simple holding policy, as it adjusts dynamically to the conditions of the system. For example, assuming some resource shortage occurs (due to bus breakdowns or drivers not showing up), based on the current available number of buses on the route, the shortest achievable headway will be used in dispatching buses from the terminals and control points, so as to maintain buses as evenly spaced as possible. The service may change back to the planned level if the resource stortage has been eliminated.

This approach is clearly different from traditional dispatching rules where buses start their trips based on predetermined schedules and cannot easily adapt to changing conditions dynamically.

Because flexible scheduling is an improved headway control "holding" policy, it should be implemented as soon as the planned headway is reduced to no more than 10 minutes (based on our customer survey) on any given day. If the planned headway increases to more than 10 minutes, other (schedule control) policies seem more appropriate. However, assume the planned headway is less than 10 minutes; if a bus breakdown occurs on a given route, the number of available buses will decrease: without flexible scheduling, the usual way to solve the problem is to assign an extra bus as soon as possible to take on the trips left by the breakdown bus. If no extra bus is currently available, the remaining trips normally assigned to that breakdown bus will be cancelled until an extra becomes available. Clearly, some longer gap (twice the planned headway) will be left in the system during this period, which will create some problems such as longer passenger waiting time, heavier passenger loads for some buses, etc. Therefore, the service level will decrease given these missing trips.

By using flexible scheduling, our goal is to solve the above problem, and to try to keep the service level as close to the planned headway as possible. A recalculation of the current achievable headway will be involved, based on the current available number of buses, according to the following formula:

Formula III.3.1 ***The achievable headway given Trecovery = 0***

$$h(a) = \frac{Ttrip(1) + Ttrip(2) + 2 \times Tlayover}{N(a)}$$

Where:

h(a) = the achievable headway, given the current number of available resources;

N(a) = the current available number of buses on a given route;

Tlayover = the minimum layover time for a given route.

This h(a) will then be used in dispatching all the buses from the terminals and other control points along the route instead of the planned headway (hp): the headway will be kept constant again according to h(a), and the goal is to keep h(a) as close as possible to hp as well as to keep the actual headways as close to h(a) as possible. Hence, immediate actions will be taken at several locations along the route dynamically, shortly after the changes in the availability in resources is reported. Therefore, no long service gap will be left in the system.

There are two aspects to look at in flexible scheduling:

First, to obtain a given service level (say hp), what is the minimum number of buses needed, and what are the excess capacities required for a reliable service? This is the off-line analysis part.

Second, how can we dynamically adjust the system in terms of h(a) according to the current available resources, in order to provide the best real-time headway control?

■Characteristics of flexible scheduling

•May result in a change of h(a) based on available resources;

•May require more or fewer resources (buses) to achieve certain levels of service frequencies;

•May be done for the current day or certain periods of the current day;

•The flow of most of the buses operated on a given route may be adjusted to maintain or restore the planned headway as much as possible during the headway control period;

In order to give a better description of this flexible scheduling policy, the following aspects should be noted:

①Flexible scheduling is mainly a headway control policy. This method is most appropriate when the planned headway is short and when schedule adherence is less important than headway adherence in service reliability. The most important performance measure used in our tests to evaluate the effectiveness of flexible scheduling policy is WF(waiting factor).

②The dispatching actions and h(a) are based on the available resources. This implies that changes to the number of available resources will result in changes of h(a). For example, on a certain route, the schedule may require 28 buses to provide a 3-minutes headway service during the peak period. Flexible scheduling may be used to control the resources to meet this service goal. But for some reasons, on a certain day, if only 26 buses are available (this may happen due to bus breakdowns or drivers not showing up), flexible scheduling may be used to calculate the h(d) which is the ***dispatching headway*** defined as the headway used in dispatching buses from the control points:

If h(a) <= hp: keep the planned headway hp, h(d)=hp;

If h(a) > hp: use h(a) as the new headway in dispatching buses from the terminals, h(d)=h(a).

We believe a better service will be provided using flexible scheduling than if two trips out of every 28 trips are cancelled as in the above example. Experimentation and analysis will be done to demonstrate the effectiveness of the flexible scheduling policy.

③In flexible scheduling, nothing is considered to be fixed, since all parameters of the problem can change, including the trip travel time for different time periods (e.g., trip travel time are usually longer during peak periods). Flexible scheduling is used to provide the best service under changing conditions.

④With flexible scheduling, the driver's capability of self-management and auto-regulation is very important. They will have to be able to follow this flexible system, and try their best to keep the headway on the route without checking to a fixed timetable. If the application of flexible scheduling causes some drivers to complete their shifts later than scheduled, drivers would be expected to cooperate with the controllers to keep the service level. Of course, they will be paid fairly.

In summary, the goal of flexible scheduling is to minimize the headway variance at the control points in order to maintain the actual service levels as close as possible to the planned service level.

Overall, we consider the flexible scheduling as a very useful and worth studying method. More details concerning this policy are given in the following subsections.

III.3.2 Assumptions in Flexible Scheduling Policy:

Before we test the effectiveness of flexible scheduling policy, some useful assumptions will be made as explained below:

- Pure flexible scheduling policy and rounded flexible scheduling policy

The value of h(a) calculated from ***formula III.3.1*** is not necessarily an integer in minutes: for example it may be 3.08 minutes or 3 minutes and 5 seconds. Realistically, it may not be very practical to use any real number as dispatching headway. Therefore, we define the ***pure flexible scheduling policy*** as the flexible scheduling using the exact h(a) as the dispatching headway h(d), i.e., h(d) = h(a). In addition to this pure flexible scheduling, we propose a variant of the flexible scheduling policy, namely the ***rounded flexible scheduling policy***, which always rounds up the h(a) to the nearest 30 seconds, and uses the rounded h(a) as the dispatching headway at the control points.

Each time the available number of buses changes (such as after a bus breakdown), h(a) is updated: it seems more practical to round h(a) up to the nearest thirty seconds and to use that value as h(d). This rounding has two benefits. First, h(d) is likely to change less often under the rounded flexible scheduling policy than under the pure flexible scheduling policy. For example, if Ttrip(1) =Ttrip(2)=45.5 minutes and Tlayover=4 minutes, then, for hp=3 we have N=33. Following the first and second breakdown respectively, we have h(d)=3.094 and h(d)=3.194 under the pure flexible scheduling policy, but h(d) remains at 3.5 under rounded flexible scheduling policy. This involves fewer changes to h(d), which facilitates the implementation of the dispatching policy and creates more stability (i.e., less sources of variability) in the system. Second, as h(d) will usually be strictly greater than h(a), this creates slack in the system (i.e., there are more available buses than what is needed at the minimum to provide service every h(d) seconds), and hence this should reduce the variability of the actual headway: it is expected that this reduction in variability will outweigh the negative impact of a longer dispatching headway as compared to the pure flexible scheduling policy in computing the average waiting time.

We have chosen to round up h(a) to the nearest 30 seconds for several reasons: first, the resulting h(d) is easier to use (3, 3.5, 4, 4.5 minutes). Second, if the rounding is too small (smaller than 30 seconds), h(d) would need to be changed more often, and it did not seem practical to hold buses for less than thirty seconds. Third, if the rounding was too large (larger than 30 seconds), buses would be held longer than necessary and the waiting time of the passengers inside the bus would become unreasonably long. We believe thirty seconds is a good compromise. Hence, for the rounded flexible scheduling policy, we set $h(d) = \lceil h(a) \rceil^{30}$, where $\lceil h(a) \rceil^{30}$ is h(a) rounded up to the nearest 30 seconds.

■In the simulation model, the pure or rounded flexible scheduling policy can be implemented at any chosen control points including the terminals, but in the real system, much information and communication would then be needed. At each control point, the information on the current dispatching headway h(d), the time since the departure of the previous bus on the given route, etc. will have to be made known. It is probably not very efficient for the controllers to manually update h(d) at all control points including the terminals, unless there exists an electronic link between the timers or the clocks at the control points so that h(d) gets updated automatically: implementing such a system may be costly. So we will do two sets of tests in the next chapter. First we will test the effectiveness of both flexible scheduling policies using two terminals as the only control points.

Second we will test the effectiveness of both flexible scheduling policies using the ***time points*** (the stops equipped with AVLC detectors) as control points. However, this policy can be tested with more control points with the simulation model.

III.3.3 Other Headway Policies May Be Needed Along the Route

In order to better achieve the stationary departure at each terminal, it seems useful to add some excess capacity or slack into the theoretical "base" system. Here we define this ***"base" system*** as: for a given planned headway during a period of day, the system consists of the minimum number of buses given by ***formula III.2.1*** to provide the planned level of service using flexible scheduling, and has a minimum amount of excess capacity or slack (due to the rounding). With this "base" system, if the bus runs early, we can hold it, but if the bus runs late and assuming no changes in the number of available resources, flexible scheduling policy cannot be used to improve the service reliability. Therefore, some other headway control policies may be needed to keep the headway constant along the route. For example, switch trips can be used to handle a very short headway between two buses where the first one is much more crowded than the second bus: let the second bus over pass the first one to pick up more passengers waiting along the route.

Section III.4

Theoretical Effectiveness of Flexible Scheduling

In this section, we will use a simple analytical argument to demonstrate that pure and rounded flexible scheduling are expected to yield more reliable service than the threshold holding policy, or, by extension, the schedule control holding policy, in the event of the reduction in the number of available resources (buses) in the system. The following analysis is done to gain insight at whether or not the two flexible scheduling policies are expected to perform better than other holding policies. We make simplifying assumptions so that the exact theoretical results are unlikely to materialize in the real system or even in simulation experiments. However, we use these results as an indicator of whether or not improvement is to be expected with flexible scheduling.

III.4.1 Assumptions and Notation

As discussed in section II.4, we assume that the planned headway is sufficiently small so that the arrival of the passengers at all stops may be modelled as a Poison process, and so that the Average Waiting Time (AWT) may be calculated using ***formula II.2.1***, in which the standard deviation of the actual headway (SD(h)) may be calculated as follows:

Formula III.4.1 Standard deviation for the sample observations:

$$S.D.(h)=\sqrt{\frac{\sum (hi-\bar{h})^2}{n-1}}$$

Where: hi = the i^{th} observation of the actual headway at a given stop;

$\bar{h}$ = the sample mean of observations of the actual headway at a given stop;

n = the number of observations (or the sample size), i = 1, 2,..., n.

The notation used in this section is summarized in table III.4.1:

Table III.4.1 Notations

Symbol	Description
hp	planned headway, in minutes
h(a)	achievable headway, the minimum headway which can be maintained given the time needed to complete the route in both direction and the number of buses available to cover the service in minutes
h(d)	dispatching headway actually used to control buses at control points for a given control policy, in minutes
N	minimum number of buses needed to provide the planned headway, defined in formula III.2.1
N(a)	the current available number of buses
AWT	Average Waiting Time, defined in formula II.2.1
WF	Waiting Factor, defined in formula II.2.2

For simplicity, we assume that all control policies are 100% effective. In other words, we do not take into account the inherent variability in the system which is a function of traffic condition, arrival rates of passengers at various stops and so on. This variability will be accounted for in the simulation model. This assumption will have major implications in our analysis and in our conclusions: we refer to this assumption as A1.

Given A1, then the actual headway between any two buses is exactly h(d). This implies that as long as N(a)>=N, h(d)=hp, AWT=0.5xhp and WF=100% for all control policies. Moreover, A1 implies that the schedule control holding policy is equivalent to the threshold headway control policy for any N(a), assuming buses leave on time from the terminals.

III.4.2 Analysis

For simplicity, and so as to better observe the impact in service deterioration following a single breakdown, we will consider the case where N(a)=N-1. The dispatching headway for the three control policies will be:

h(d)=hp	for the threshold policy
h(d)=N*hp/(N-1)=h(a)	for the pure flexible scheduling policy
$h(d)=[h(a)]^{30}$	for the rounded flexible scheduling policy

It follows that for the rounded flexible scheduling policy, if h(a)<(hp+0.5), then h(d)=hp+0.5 (in minutes). This condition is met if:

$$hp<0.5(N-1)=h1 \qquad (1)$$

For OC Transpo Route 95, this condition is true if $hp \leq 5$ minutes. Note that h(d) = hp + 1 if hp + 0.5 < h(a) <= hp + 1, or equivalently, if

$$h1 = 0.5(N-1) < hp < N-1 = h2 \qquad (2)$$

The fact that h(d) changes as a result of the breakdown does not imply that the actual headway will automatically become h(d) under the two flexible scheduling policies: in the real system, there will be a transition period which corresponds to the time it takes for the (N-1) remaining buses to go through one of the control points. The duration of this transition period is much shorter if there are several control points. We will consider what happens after the transition period (or in the longer run): this is also equivalent to assuming all stops are control stops.

A■Computing the (long run) value of h at any stop:

- Threshold policy:

$$\bar{h}=\frac{(N-2)hp+2hp}{N-1}=h(a)$$

- Pure flexible scheduling policy:

$$\bar{h}=h(a)$$

- Rounded flexible scheduling policy:

h=hp+0.5 if hp≤h1

h=hp+1 if hp>h1

B■Computing the (long run) ***standard deviation*** at any stop:

- Threshold policy:

$$S.D.(h)=\sqrt{\frac{(N-2)(hp-h(a))^2+(2hp-h(a))^2}{N-2}}=\sqrt{\frac{(N-2)hp^2}{(N-1)(N-2)}}=\frac{hp}{\sqrt{N-1}}$$

- Pure and rounded flexible scheduling policies:

S.D.(h) = 0.

C■Computing the (long run) Average Waiting Time at any stops:

- Threshold policy:

$$AWT=\frac{N\times hp}{2(N-1)}\left[1+\frac{\frac{hp}{\sqrt{N-1}}}{\frac{N\times hp}{N-1}}\right]^2=\frac{N\times hp}{2(N-1)}\left(1+\frac{\sqrt{N-1}}{N}\right)^2=\frac{h(a)}{2}\left(1+\frac{\sqrt{N-1}}{N}\right)^2$$

•Pure flexible scheduling policy:

$$AWT(P)=\frac{N\times hp}{2(N-1)}=\frac{h(a)}{2}$$

•Rounded flexible scheduling policy:

$AWT = (hp + 0.5) / 2$ if $hp \le h1$;

$AWT = (hp + 1) / 2$ if $h1 < hp \le h2$.

D■Computing the (long run) Waiting Factor at any stops:

•Threshold policy:

$$WF=\frac{N}{N-1}(1+\frac{\sqrt{N-1}}{N})^2\times 100\%$$

•Pure flexible scheduling policy:

$$WF=\frac{N}{N-1}\times 100\%$$

•Rounded flexible scheduling policy:

$WF = (1+0.5/hp) \times 100\%$ if $hp \le h1$;

$WF = (1 + 1/hp) \times 100\%$ if $h1 < hp \le h2$.

While it seems that the expected WF under the threshold and pure flexible scheduling policies are independent of hp, note that N is function of hp: if hp increases, N decreases so that for larger hp, rounded flexible scheduling may provide more reliable service (with respect to WF) as WF would increase for both the threshold and pure flexible scheduling policies. However, pure flexible scheduling is expected to provide better service than threshold: in fact, the improvement in WF compared to the WF under the threshold policy is expected to be:

$$Improvement(PureFle.Sch.vsThre.)=1-\frac{N^2}{N+\sqrt{N-2}}>0$$

and the improvement decreases with increasing N (or decreasing hp). This makes sense as service is not expected to deteriorate as much following the breakdown of one bus if N is large: the variability in headway is not large.

Comparing rounded flexible scheduling with threshold, we note that the former provides a better WF :

If $hp \leq h1$:

$$hp > \frac{N-1}{2[N(1+\frac{\sqrt{N-2}}{N})^2-N+1]}$$

If $h1 < hp \leq h2$: (3)

$$hp > \frac{N-1}{N(1+\frac{\sqrt{N-2}}{N})^2-N+1}$$

It can be shown that (2) is met if the following holds:

$hp > (N^{1/2})/4$ if $hp \leq h1$; (4)

$hp > (N^{1/2})/2$ if $h1 < hp \leq h2$;

If T represents the combined travel time and layover time associated with one average length trip for the bus route (given trip lengths in both direction and different trip patterns) and ignoring the rounding, N=T/hp. Table III.4.2 shows the values of hp such that the rounded flexible scheduling policy will yield some improvement in WF compared to the threshold policy following one bus breakdown, as a function of T.

As shown in this table, improvement is expected under most practical situations as hp is rarely smaller than 2 minutes, and T is rarely outside the range [20, 90] minutes. Hence, despite a large expected headway associated with the rounded flexible scheduling (compared with threshold), improvement in average waiting time is expected as the variability of the headway is reduced with that policy: controlling variability is expected to yield positive results.

Three headway control policies, namely threshold, pure flexible scheduling and rounded flexible scheduling will be tested through simulation in the next chapter.

Table III.4.2 Range in hp for Expected Improvement

T	h1	0≤ hp≤ h1
20	2.93	[1.08, h1]
30	3.63	[1.24, h1]
40	4.23	[1.36, h1]
50	4.76	[1.47, h1]
60	5.23	[1.56, h1]
70	5.67	[1.64, h1]
80	6.08	[1.71, h1]
90	6.46	[1.78, h1]

IV. Experimentation and Results

IV.1 Experimental Situation

■Trip patterns of Route 95

OC Transpo Route 95 is a complex route which has four types of trip patterns:

- Eastbound:

From: Baseline Station	To: Blair Station	(short pattern)
From: Baseline Station	To: Place D'Orléans	(long pattern)

- Westbound:

From: Blair Station	To: Baseline Station	(short pattern)
From: Place D'Orléans	To: Baseline Station	(long pattern)

Every second eastbound trip ends at Place D'Orléans (which is further east than Blair station) in periods of high frequency (i.e., when the planned headway is no more than five minutes). For those periods, the planned headway for the stops between Blair station and Place D'Orléans is twice as long as the planned headway for the rest of the route, but is still short enough (no more than ten minutes) to make headway control desirable according to our survey.

■After the design and programming of flexible scheduling into the control module, two sets of experiments have been done, which are:

Set A: Using two terminals as the only control points

We decided to choose Baseline station for eastbound trips and Blair station for westbound trips as our control terminals in our tests because all the buses pass by these two stops: hence the headway control actions (irrespective of the control policy) will only take place at these two terminals.

Set B: Using the time points as control points

In our simulation model, out of the 50 stops in both directions on Route 95 (25 for each direction), there are 12 time points. Recently, OC Transpo has changed their schedule, some stops, and has implemented more AVLC detectors on the Transitway since the development of the simulation model. Given the updated data files were not available at present, our experiments are still based on the old data, which are however very similar to the current situation.

The 12 time points can be identified by those stops which are marked by "*" on the stop name list in appendix VII.6 "Stops on Route 95 in the simulation model".

■Before presenting those control policies to be tested, we repeat the equation that can be used to calculate the achievable headway h(a), as presented in chapter III, *formula III.3.1*:

$$h(a)=\frac{Ttrip(1)+Ttrip(2)+2\times Tlayover}{N(a)}$$

***Where*:**

h(a) = the achievable headway, given the number of resources currently available;

N(a) = the number of buses that are currently available on a given route.

Given Route 95 is composed of four trip patterns, this equation must be modified. The following table gives the planned travel time of the four trip patterns during the AM peak period as found in the simulation schedule data files:

Table IV. 1.1 The Travel Time of Each Pattern During AM Peak Period

Direction	Long pattern travel time	Short pattern travel time
Eastbound	54 minutes	37 minutes
Westbound	54 minutes	37 minutes

Given the fact that most of the buses do one long trip and then do one short trip, the average travel time can be represented as:

Trip Travel Time = 54+37 = 91 (minutes)

The default minimum layover time in the simulation model is 4 minutes in the simulation model, and 33 buses are operating in the AM peak period. When all the booked buses are operating on the route, h(a) = (91+2*4)/33 = 3. 0 minutes, which shows that the planned bus number will just be enough to cover the planned service level, which is three minutes, if no breakdown occurs.

■For each set of experiments, three control policies (as we discussed in section III.4) have been tested. They are:

① Pure Flexible Scheduling Policy

Calculate the achievable headway h(a) from ***formula III.3.1***, and compare h(a) and the planned headway hp: change the dispatching headway used to control the departure of buses at control points from hp to h(a) as soon as h(a) is greater than hp;

② Rounded Flexible Scheduling Policy

This is the second variant to flexible scheduling as we discussed in section III.4.3. As the number of available buses changes, h(d) is set to be equal to $[h(a)]^{30}$.

③ Threshold Policy

The threshold policy consists in holding a bus leaving a control point if the headway between this bus and the previous bus is less than the planned headway. Threshold policy is the simplest headway control policy. By using the threshold policy, the planned headway will be kept constant during the whole period of the test, even if breakdowns occur. Hence for the threshold policy, the dispatching headway is always be kept as the planned headway (i.e., h(d)=hp). We proposed in chapter III that flexible scheduling could be an effective way to handle bus breakdowns with high-frequency service level, therefore, we decided to compare flexible scheduling policies with threshold policy which has already been shown to be effective in improving service during short headway periods.

■We considered comparing these three headway control policies with the schedule control holding policy, as done in [5], since this policy is a fair representation of the current control policy used in most transit agencies, and at OC Transpo in particular. However, in order to observe a difference between the threshold and flexible scheduling policies, we needed to increase drastically the bus breakdown probability in the simulation model. Despite this increase, we were not able to obtain as many breakdowns in the simulation runs using the "schedule control" scenario than under the three headway control policies, so that the comparison would have been awkward and biased in favour of schedule control. Furthermore, given it had been shown that the threshold policy was clearly more effective than the schedule control holding policy when no bus breakdown was allowed in [5], and given the main objective of this thesis is to study headway control policies, we decided not to pursue the comparison with the schedule control holding policy.

■For each test, AM peak period has been chosen (from 7:00 AM to 9:00 AM) given the following reasons:

①Previous sensitivity analysis has shown that the simulation results for the AM peak period will be more indicative of expected behaviour of the real system than any other period of the day [5];

②The AM peak period is a high-frequency service period as required for headway control: the planned headway is 3 minutes during this period.

③Before 7:00 AM and after 9:00 AM, the service level changes so that the planned headway may vary during the transition periods. In order to better measure the effectiveness of the various control policies, we want to run the experiments over a time period during which the planned headway and the scheduled number of buses are constant, so as to avoid transition period where blocks are introduced or removed. For the AM peak period, our needs are met (at 7:00 AM, there are 29 buses on the route, but this number increases to 33 shortly after 7:00 AM and is kept at the level until 9:00 AM).

■For each set of the experiments, given the same random seed, the three different control policies yield:

①Identical results if no breakdown occurs;

②The time of the first breakdown is the same, if some breakdowns occur;

③The time and total number of bus breakdowns is not necessarily the same during the test period, which means that from 7:00 AM to 9:00 AM, one policy may give more breakdowns than the other two policies. As soon as h(d) changes, the control action taken under the three control policies will differ. This changes the order in which the various events (in the simulation event table) will be processed so that it is no longer the same random number which will be used to generate bus breakdowns. This also reflects the real situations in a certain way: in a dynamic setting, by taking a given action, the set of possible future outcomes is generally different than if a different action had been taken.

■The goal of these experiments is to test the effectiveness of flexible scheduling when the available resources changed. Therefore, we set the probability of a bus breakdown much higher than the simulation default to try to have at least one bus breakdown during our test period. However, if there is at least one bus breakdown, the difference in the results may be explained by the application of different control policies. Hence, we propose that these results be treated as paired-observations given the same random seed are used. As suggested in [2], tests based on paired-observations will "remove much of the extraneous variation", thus will allow us to concentrate on the target factor which in our case is the effectiveness of different control policies.

Hence, in each set of experiments and for each random seed, three control policies will be applied, and the results will be paired as follows for our analysis:

- Pure flexible scheduling vs threshold
- Rounded flexible scheduling vs threshold
- Pure flexible scheduling vs rounded flexible scheduling

■ The analysis will first be done for each stop, and six (two sets×three pairs) statistical analyses using MINITAB based on six pairs of observations will be provided. Finally, an overall test for all the 50 stops on the route will be given to show the effectiveness of different control policies. For each random seed and for each control policy, 40 test runs have been done.

IV.2 Statistical Basis for the Analysis

According to [2], two tests have been chosen as our statistical tools for our analysis:

■ **The Wilcoxon Signed-Rank Test**

Assumptions

•Paired-observations;

•The distribution of the difference between the two populations is symmetric.

Hypothesis

Null hypothesis	Ho:	$\mu 1 \leq \mu 2$;
Alternative hypothesis	Hi:	$\mu 1 > \mu 2$.

$\mu 1$ and $\mu 2$ are the means of the two populations.

Wilcoxon T Statistic

$$T = \min (\Sigma (+), \Sigma (-))$$

Where

T = the smaller of the two sums of ranks;

$\Sigma(+)$ = the sum of the ranks of the positive difference between the paired-observation;

$\Sigma(-)$ = the sum of the ranks of the negative difference between the paired-observation.

- **The Paired-observation *t* Test**

Assumptions

•Paired-observations;

•The population of differences between the paired-observation is normally distributed.

Paired-observation t Test Statistic

$$t=\frac{\bar{D}-\mu Do}{Sd/\sqrt{n}}$$

Where

$\bar{D}$ = the sample average difference between each paired-observation;

Sd = the sample standard deviation of Di's;

n = the sample size, the number of pairs of observation;

μDo = the population mean difference under the null hypothesis.

Hypothesis

Ho: $\mu Do \le 0$;

H1: $\mu Do > 0$.

When the null hypothesis is true and the population mean difference is μD, the statistic has a t distribution with n-1 degree of freedom.

For both of the two statistics, the ***P-value*** will be recorded and will be analysed.

IV.3 Analysis of the Distributions and the Number of Breakdowns

- The distributions of the differences between the paired-observations

Since our sample is not large, it is difficult to identify the data distribution. However, if the results from the two tests agree with each other, we will be confident in our results.

- Number of bus breakdowns in the test

Since the total number of bus breakdowns may not be the same using different control policies, this may have an impact on the results of the tests if the number of bus breakdowns is not comparable. The number of bus breakdowns for the 40 runs are shown below:

Table IV.3.1 Number of Bus Breakdowns

Control Policy	Pure Fle. Sch.	Threshold	Rounded Fle. Sch.	Total
Two Terminals	76	68	69	213
Time Points	75	60	69	204
Total	151	128	138	417

Let T, R and P represent the number of bus breakdown for a same random seed under the Threshold, Rounded Flexible Scheduling and Pure Flexible Scheduling policies respectively. For the 40 simulation runs we obtained the following results:

Table IV.3.2 Comparisons of the Number of Bus Breakdowns

Comparisons	P=T	R=T	P=R	P>T	R>T	P>R
2 Terminals	in 20 runs	in 17 runs	In 20 runs	in 14 runs	in 13 runs	in 11 runs
Time Points	in 18 runs	in 19 runs	in 21 runs	in 14 runs	in 10 runs	in 11 runs

We can see that the total number of the two sets of tests is comparable, and on average there were more bus breakdowns simulated under the flexible scheduling policies, which implies that if we can show an improvement in service from the application of flexible scheduling based on our tests, it is a stronger indication that this policy is effective despite the large number of bus breakdowns, and that the improvement would have been more marked had the number of bus breakdowns been the same as for the threshold policy. There is no evidence showing that there exists a fixed pattern of the number of bus breakdowns such as there is systematically more breakdowns under one policy than under another policy.

IV.4 Analysis of the Results

In order to test the effectiveness of flexible scheduling and to show there is an improvement in the service by using flexible scheduling, we have done the following analysis:

☞Please note that all the Waiting Factors are based on the planned headway, which in our case is 3 minutes.

■Analysis 1: Two Terminals, Pure flexible scheduling vs Threshold

Let $\mu 1$= the population mean of Waiting Factors (WF) using pure flexible scheduling;

Let $\mu 2$= the population mean of WF's using threshold;

Let $\mu Do = \mu 1 - \mu 2$.

- *For t test and for Wilcoxon test*:

Ho: $\mu Do \geq 0$;

H1: $\mu Do < 0$.

- *Decision rules*:

$\alpha = 0.15$;

A represents that the two tests (t-test and the w-test) agree that Pure Flexible Scheduling is BETTER;
B represents that the two tests agree that Threshold is BETTER;
C represents that none of the policies is significantly better.

- *Display of the Statistical Analysis:*

Table IV.4.1 Results of the tests for analysis 1 with P-value shown

Stops	T test (p-value)	W test (p-value)	Decisions
1- SH935* Baseline	0.02	0.005	A
2- SJ970	0.09	0.064	A
3-SJ920	0.14	0.078	A
4-NI915	0.12	0.128	A
5-NC930	0.05	0.013	A
6-NA930	0.06	0.036	A
7-CJ920	0.04	0.006	A
8-CJ930	0.05	0.045	A
9-CJ010	0.02	0.011	A

Table IV.4.1 Results of the tests for analysis 1 with P-value shown

10-CA940	0.02	0.011	A
11-CA950	0.00	0.000	A
12-CB960	0.00	0.000	A
13-CB970	0.00	0.000	A
14-CD900	0.01	0.001	A
15-CD955	0.01	0.013	A
16-CD975	0.04	0.039	A
17-CE920	0.03	0.065	A
18-AF910	0.09	0.284	C
19-AE910	0.54	0.305	C
20-EB915	0.07	0.082	A
21-EC910	0.33	0.266	C
22-EE905	0.32	0.165	C
23-EK566	0.48	0.314	C
24-EM020	0.79	0.496	C
25-EM090	0.71	0.780	C
26-EJ035	0.36	0.001	C
27-EM010	0.33	0.051	C
28-EM015	0.21	0.071	C
29-EK564	0.15	0.006	A
30-EG001	0.86	0.789	C
31-EE915	0.74	0.707	C
32-EC900*Blair Westbound	0.34	0.551	C
33-EB905	0.32	0.519	C
34-AE900	0.55	0.734	C
35-AF950	0.51	0.497	C
36-CE940	0.43	0.460	C
37-CD985	0.40	0.433	C
38-CD965	0.31	0.431	C
39-CD915	0.22	0.172	C

Table IV.4.1 Results of the tests for analysis 1 with P-value shown

40-CB900	0.48	0.561	C
41-CB910	0.921	0.880	B
42-CA920	0.79	0.905	C
43-CA930	0.83	0.800	C
44-CJ020	0.933	0.780	C
45-CJ900	0.953	0.889	B
46-NA910	0.89	0.776	C
47-NC910	0.87	0.768	C
48-NI910	0.12	0.112	A
49-SJ900	0.15	0.102	A
50-SJ960	0.13	0.091	A

- *Results (with number of each class shown):*

A	B	C
22	2	26

- *Conclusions:*

① Our tests show that for 44% of all the stops, Pure Flexible Scheduling is more effective than Threshold (smaller Waiting Factor), while for 52% of all the stops the tests can not determine which policy is more effective with respect to the WF's;

② At terminals, the pure flexible scheduling is more effective than threshold;

③ Pure flexible scheduling seems more effective than threshold if we use the two terminals as control points.

■Analysis 2: Two Terminals, Rounded flexible scheduling vs Threshold

Let $\mu 1$= the population mean of Waiting Factors using rounded flexible scheduling;

Let $\mu 2$= the population mean of WF's using threshold;

Let $\mu Do = \mu 1 - \mu 2$.

- For t test and for Wilcoxon test:

  Ho: $\mu Do \geq 0$;

  H1: $\mu Do < 0$.

- *Decision rules:*

$\alpha = 0.15$;

A represents that the two tests agree that Rounded Flexible Scheduling is BETTER;
B represents that the two tests agree that Threshold is BETTER;
C represents that none of the policies is significantly better.

- *Display of the Statistical Analysis:*

Table IV.4.2 Results of the tests for analysis 2 with P-value shown

Stops	T test (p-value)	W test (p-value)	Decisions
1- SH935* Baseline	0.00	0.000	A
2- SJ970	0.00	0.000	A
3-SJ920	0.00	0.000	A
4-NI915	0.01	0.000	A
5-NC930	0.01	0.000	A
6-NA930	0.00	0.000	A
7-CJ920	0.00	0.002	A
8-CJ930	0.00	0.001	A
9-CJ010	0.00	0.001	A
10-CA940	0.00	0.000	A
11-CA950	0.00	0.000	A
12-CB960	0.00	0.000	A
13-CB970	0.00	0.000	A
14-CD900	0.00	0.000	A
15-CD955	0.00	0.005	A
16-CD975	0.01	0.017	A

Table IV.4.2 Results of the tests for analysis 2 with P-value shown

17-CE920	0.00	0.005	A
18-AF910	0.00	0.010	A
19-AE910	0.08	0.080	A
20-EB915	0.00	0.001	A
21-EC910	0.02	0.033	A
22-EE905	0.06	0.022	A
23-EK566	0.07	0.021	A
24-EM020	0.59	0.263	C
25-EM090	0.56	0.639	C
26-EJ035	0.26	0.001	C
27-EM010	0.25	0.003	C
28-EM015	0.20	0.006	C
29-EK564	0.24	0.273	C
30-EG001	0.39	0.258	C
31-EE915	0.02	0.001	A
32-EC900*Blair Westbound	0.10	0.022	A
33-EB905	0.09	0.016	A
34-AE900	0.11	0.022	A
35-AF950	0.11	0.025	A
36-CE940	0.07	0.010	A
37-CD985	0.06	0.010	A
38-CD965	0.05	0.012	A
39-CD915	0.02	0.003	A
40-CB900	0.05	0.014	A
41-CB910	0.27	0.175	C
42-CA920	0.25	0.232	C
43-CA930	0.32	0.317	C
44-CJ020	0.49	0.487	C
45-CJ900	0.40	0.481	C
46-NA910	0.32	0.583	C

Table IV.4.2 Results of the tests for analysis 2 with P-value shown

47-NC910	0.36	0.439	C
48-NI910	0.11	0.109	A
49-SJ900	0.26	0.371	C
50-SJ960	0.31	0.302	C

- *Results (with number of each class shown):*

A	B	C
34	0	16

- *Conclusions:*

① Our tests show that for 68% of all the stops, the rounded flexible scheduling yields a smaller WF than the threshold policy;

② At terminals, the service provided by using the rounded flexible scheduling is better than under the threshold policy;

③ Rounded flexible scheduling seems more effective than threshold if we use the two terminals as control points.

■Analysis 3: Two Terminals, Rounded flexible scheduling vs Pure flexible scheduling

Let $\mu 1$= the population mean of Waiting Factors using pure flexible scheduling;

Let $\mu 2$= the population mean of WF's using rounded flexible scheduling;

Let $\mu Do = \mu 2 - \mu 1$.

- For t test and for Wilcoxon test:

Ho: $\mu Do \geq 0$;

H1: $\mu Do < 0$.

- *Decision rules:*

$\alpha = 0.15$;

A represents that the two tests agree that Rounded Flexible Scheduling is BETTER;
B represents that the two tests agree that Pure Flexible Scheduling is BETTER;
C represents that none of the policies is significantly better.

- *Display of the Statistical Analysis:*

Table IV.4.3 Results of the tests for analysis 3 with P-value shown

Stops	T test (p-value)	W test (p-value)	Decisions
1- SH935* Baseline	0.0002	0.000	A
2- SJ970	0.0083	0.000	A
3-SJ920	0.011	0.000	A
4-NI915	0.041	0.019	A
5-NC930	0.21	0.06	C
6-NA930	0.086	0.026	A
7-CJ920	0.12	0.011	A
8-CJ930	0.11	0.006	A
9-CJ010	0.077	0.014	A
10-CA940	0.059	0.009	A
11-CA950	0.053	0.020	A
12-CB960	0.078	0.038	A
13-CB970	0.086	0.032	A
14-CD900	0.030	0.031	A
15-CD955	0.031	0.023	A
16-CD975	0.035	0.027	A
17-CE920	0.044	0.035	A
18-AF910	0.019	0.010	A
19-AE910	0.028	0.017	A
20-EB915	0.002	0.000	A

Table IV.4.3 Results of the tests for analysis 3 with P-value shown

21-EC910	0.010	0.039	A
22-EE905	0.088	0.107	C
23-EK566	0.062	0.039	A
24-EM020	0.21	0.193	C
25-EM090	0.40	0.31	C
26-EJ035	0.31	0.057	C
27-EM010	0.31	0.137	C
28-EM015	0.36	0.208	C
29-EK564	0.44	0.747	C
30-EG001	0.17	0.192	C
31-EE915	0.019	0.009	A
32-EC900*Blair Westbound	0.11	0.005	A
33-EB905	0.097	0.054	A
34-AE900	0.083	0.048	A
35-AF950	0.10	0.107	A
36-CE940	0.096	0.059	A
37-CD985	0.099	0.104	A
38-CD965	0.11	0.094	A
39-CD915	0.080	0.053	A
40-CB900	0.069	0.036	A
41-CB910	0.098	0.046	A
42-CA920	0.11	0.022	A
43-CA930	0.14	0.080	A
44-CJ020	0.11	0.152	C
45-CJ900	0.080	0.125	A
46-NA910	0.11	0.162	C
47-NC910	0.14	0.236	C
48-NI910	0.39	0.386	C
49-SJ900	0.56	0.551	C
50-SJ960	0.57	0.593	C

- *Results (with number of each class shown):*

A	B	C
35	0	15

- *Conclusions:*

① Our tests show that with two terminals as the only control points, 70% of all the stops show a better service (as far as the WF's are concerned) using the rounded flexible scheduling than using the pure flexible scheduling. This suggests that, with a small number of control points, a little more slack in the system (resulting from the rounding) will actually improve the service;

②Rounded flexible scheduling seems to give a marginally better service than the pure flexible scheduling when using the two terminals as control points.

Conclusions for the above three analysis with two terminals as only control points:

①Some slack in the system may improve the service, and may also allow the flexible scheduling policies to have a better service control;

②Rounding the available headway h(a) to the nearest 30 seconds seems to be the best choice among the three control policies when using the two terminals as control points. This is probably because in such a short test period (two hours), and relatively long transition periods following the change in h(a), it is easier to adapt to a larger h(d) which provides more slack to absorb the variability in headway.

In the three following analyses, the time points are used as control points: the control stops are marked with an asterisk (*) in the results tables.

■Analysis 4: Time Points, Pure flexible scheduling vs Threshold

Let $\mu 1$=, the population mean of Waiting Factors using pure flexible scheduling;

Let $\mu 2$= the population mean of WF's using threshold;

Let $\mu Do = \mu 1 - \mu 2$.

- For t test and for Wilcoxon test:

Ho: $\mu Do \geq 0$;

H1: $\mu Do < 0$.

- ***Decision rules:***

$\alpha = 0.15$;

A represents that the two tests agree that Pure Flexible Scheduling is BETTER;
B represents that the two tests agree that Threshold is BETTER;
C represents that none of the policies is significantly better.

- *Display of the Statistical Analysis:*

Table IV.4.4 Results of the tests for analysis 4 with P-value shown

Stops	T test (p-value)	W test (p-value)	Decisions
1- SH935*	0.01	0.010	A
2- SJ970	0.08	0.084	A
3-SJ920	0.01	0.006	A
4-NI915	0.00	0.007	A
5-NC930*	0.06	0.033	A
6-NA930	0.23	0.104	C
7-CJ920	0.28	0.239	C
8-CJ930*	0.44	0.460	C
9-CJ010	0.00	0.001	A
10-CA940	0.60	0.327	C
11-CA950	0.11	0.056	A
12-CB960	0.09	0.166	C
13-CB970	0.02	0.078	A
14-CD900	0.02	0.018	A
15-CD955	0.07	0.093	A
16-CD975*	0.01	0.013	A
17-CE920	0.00	0.004	A
18-AF910	0.33	0.166	C
19-AE910	0.06	0.034	A
20-EB915	0.04	0.034	A

Table IV.4.4 Results of the tests for analysis 4 with P-value shown

21-EC910	0.13	0.071	A
22-EE905*	0.65	0.804	C
23-EK566	0.61	0.500	C
24-EM020	0.03	0.022	A
25-EM090	0.49	0.506	C
26-EJ035*	0.27	0.002	C
27-EM010*	0.27	0.011	C
28-EM015	0.09	0.004	A
29-EK564	0.14	0.114	A
30-EG001	0.05	0.013	A
31-EE915*	0.01	0.011	A
32-EC900	0.00	0.000	A
33-EB905	0.02	0.008	A
34-AE900	0.09	0.008	A
35-AF950	0.01	0.006	A
36-CE940	0.03	0.008	A
37-CD985*	0.03	0.005	A
38-CD965	0.01	0.002	A
39-CD915	0.00	0.000	A
40-CB900	0.00	0.000	A
41-CB910	0.05	0.051	A
42-CA920	0.01	0.019	A
43-CA930	0.00	0.001	A
44-CJ020	0.34	0.093	C
45-CJ900*	0.04	0.001	A
46-NA910	0.00	0.001	A
47-NC910*	0.00	0.001	A
48-NI910	0.00	0.003	A
49-SJ900	0.00	0.000	A
50-SJ960	0.00	0.001	A

- *Results (with number of each class shown):*

A	B	C
38	0	12

- *Conclusions:*

① Using the default time points as control points, our tests show that 76% of all the stops show better service (decrease in the Waiting Factor) by using pure flexible scheduling compared to threshold, which is higher than the results obtained when using the two terminals as control points (44% in our tests): therefore, this suggests that by increasing the number of control points, the pure flexible scheduling policy is expected to be even more effective in decreasing the WF's;

② At all the control points, the pure flexible scheduling is more effective than threshold in reducing WF;

③Pure flexible scheduling is more effective than threshold if we use the time points as control points.

■Analysis 5: Time Points, Rounded flexible scheduling vs Threshold

Let $\mu 1$=, the population mean of Waiting Factors using rounded flexible scheduling;

Let $\mu 2$= the population mean of WF's using threshold;

Let $\mu Do = \mu 1 - \mu 2$.

- For t test and for Wilcoxon test:

Ho: $\mu Do \geq 0$;

H1: $\mu Do < 0$.

- *Decision rules:*

$\alpha = 0.15$;

A represents that the two tests agree that Rounded Flexible Scheduling is BETTER;
B represents that the two tests agree that Threshold is BETTER;
C represents that none of the policies is significantly better.

- *Display of the Statistical Analysis:*

Table IV.4.5 Results of the tests for analysis 5 with P-value shown

Stops	T test (p-value)	W test (p-value)	Decisions
1- SH935*	0.00	0.000	A
2- SJ970	0.00	0.000	A
3-SJ920	0.00	0.001	A
4-NI915	0.00	0.001	A
5-NC930*	0.67	0.831	C
6-NA930	0.85	0.903	B
7-CJ920	0.81	0.816	C
8-CJ930*	0.98	0.99	B
9-CJ010	0.08	0.102	A
10-CA940	0.98	0.999	B
11-CA950	0.15	0.123	A
12-CB960	0.22	0.232	C
13-CB970	0.03	0.008	A
14-CD900	0.09	0.096	A
15-CD955	0.44	0.375	C
16-CD975*	0.53	0.586	C
17-CE920	0.45	0.408	C
18-AF910	0.42	0.397	C
19-AE910	0.99	0.98	B
20-EB915	0.15	0.204	C
21-EC910	0.00	0.000	A
22-EE905*	0.99	0.999	B
23-EK566	0.99	0.996	B
24-EM020	0.15	0.114	A
25-EM090	0.29	0.366	C
26-EJ035*	0.00	0.000	A
27-EM010*	0.01	0.003	A
28-EM015	0.02	0.004	A

Table IV.4.5 Results of the tests for analysis 5 with P-value shown

29-EK564	0.01	0.006	A
30-EG001	0.02	0.015	A
31-EE915*	0.00	0.000	A
32-EC900	0.00	0.002	A
33-EB905	0.00	0.000	A
34-AE900	0.00	0.000	A
35-AF950	0.00	0.000	A
36-CE940	0.00	0.005	A
37-CD985*	0.00	0.006	A
38-CD965	0.00	0.001	A
39-CD915	0.00	0.001	A
40-CB900	0.01	0.001	A
41-CB910	0.02	0.004	A
42-CA920	0.05	0.016	A
43-CA930	0.02	0.018	A
44-CJ020	0.00	0.003	A
45-CJ900*	0.02	0.045	A
46-NA910	0.00	0.002	A
47-NC910*	0.03	0.106	A
48-NI910	0.94	0.916	B
49-SJ900	0.24	0.329	C
50-SJ960	0.27	0.040	C

- *Results (with number of each class shown):*

A	B	C
32	7	11

- *Conclusions:*

① Using the time points as the control points, our tests show that for 64% of all the stops, rounded flexible scheduling is more effective in decreasing the waiting factor than threshold policy, which is slightly lower than the percentage observed (68%) using two terminals as the only control points. However, the threshold policy is now more effective for 14% of the stops: therefore, increasing the number of control points seem to increase the effectiveness of the threshold policy more than it does the effectiveness of the rounded flexible scheduling policy;

②Rounded flexible scheduling policy is not more effective than threshold at all the control points;

③ Rounded flexible scheduling still is more effective in keeping WF small than threshold overall when we use the time points as control points.

■Analysis 6: Time Points, Pure flexible scheduling vs Rounded flexible scheduling

Let $\mu 1$= the population mean of Waiting Factors using pure flexible scheduling;

Let $\mu 2$= the population mean of WF's using rounded flexible scheduling;

Let $\mu D = \mu 1 - \mu 2$.

- For t test and for Wilcoxon test:

Ho: $\mu D \geq 0$;

H1: $\mu D < 0$.

- *Decision rules:*

$\alpha = 0.15$;

A represents that the two tests agree that Rounded Flexible Scheduling is BETTER;
B represents that the two tests agree that Pure Flexible Scheduling is BETTER;
C represents that none of the policies is significantly better.

- *Display of the Statistical Analysis:*

Table IV.4.6 Results of the tests for analysis 6 with P-value shown

Stops	T test (p-value)	W test (p-value)	Decisions
1- SH935*	0.000	0.000	A

Table IV.4.6 Results of the tests for analysis 6 with P-value shown

2- SJ970	0.0030	0.010	A
3-SJ920	0.512	0.28	C
4-NI915	0.34	0.642	C
5-NC930*	0.99	0.994	B
6-NA930	0.97	0.981	B
7-CJ920	0.95	0.978	B
8-CJ930*	1.00	0.999	B
9-CJ010	0.90	0.911	B
10-CA940	0.99	0.994	B
11-CA950	0.71	0.787	C
12-CB960	0.77	0.800	C
13-CB970	0.72	0.673	C
14-CD900	0.92	0.938	B
15-CD955	0. 93	0.934	B
16-CD975*	1.00	1.000	B
17-CE920	1.00	0.999	B
18-AF910	0.65	0.842	C
19-AE910	1.00	1.000	B
20-EB915	0.858	0.86	B
21-EC910	0.14	0.204	C
22-EE905*	0.98	0.997	B
23-EK566	0.98	0.995	B
24-EM020	0.81	0.852	C
25-EM090	0.34	0.045	C
26-EJ035*	0.043	0.045	A
27-EM010*	0.086	0.142	A
28-EM015	0.15	0.117	A
29-EK564	0.057	0.135	A
30-EG001	0.42	0.477	C
31-EE915*	0.018	0.066	A

Table IV.4.6 Results of the tests for analysis 6 with P-value shown

32-EC900	0.98	0.982	B
33-EB905	0.14	0.454	C
34-AE900	0.10	0.358	C
35-AF950	0.32	0.609	C
36-CE940	0.38	0.699	C
37-CD985*	0.37	0.668	C
38-CD965	0.32	0.575	C
39-CD915	0.72	0.823	C
40-CB900	0.80	0.871	C
41-CB910	0.38	0.673	C
42-CA920	0.64	0.719	C
43-CA930	0.90	0.894	B
44-CJ020	0.13	0.364	C
45-CJ900*	0.70	0.996	C
46-NA910	0.76	0.998	C
47-NC910*	0.93	1.000	B
48-NI910	1.00	1.000	B
49-SJ900	1.00	1.000	B
50-SJ960	0.99	0.999	B

- *Results (with number of each class shown):*

A	B	C
7	21	22

- *Conclusions:*

① Our tests show that with the time points as the only control points, 42% of all the stops give a better service (as far as the WF's are concerned) using the pure flexible scheduling than using the rounded flexible scheduling. This shows that, with more control points, it seems preferable not to round up h(a) as the variability of headway does not seem to be large enough to warrant so much slack (probably due to the tighter control) and because the transition period is now much shorter (i.e., the time it takes for all buses to be dispatched from a control point using h(d)). For example, if there was only one bus breakdown during the whole testing period, and the breakdown occurred shortly after 7:00 AM, in rounded flexible scheduling h(d)=3.5 minutes instead of h(a) which is 3.0833 minutes, thus some slack would be built into the system. The more the control points, the tighter control of the system, therefore, the less variability in the system. This can be better illustrated if all the stops are used as control points, the headway at all the stops will be controlled at 3.5 minutes using the rounded flexible scheduling, but since 3.0833 minutes is the achievable headway, some service resources will be wasted due to this longer dispatching headway. The average headway has more impact on AWT than variability in the headway which is almost null in both cases;

②Using the time points as control points, benefits should be achieved at all the control points if the pure flexible scheduling is used, while the benefits of using the rounded flexible scheduling will not be as large.

Conclusion for the above three analyses:

Pure flexible scheduling using the achievable headway h(a) to handle bus breakdowns with high-frequency service is the best choice among the three control policies when the time points are used as control points. For easy implementation, the rounded flexible scheduling is also considered as a better policy than threshold in this case.

■ Overall Effectiveness

To find out the overall effectiveness of the two flexible scheduling policies compared to the threshold policy, we have done a sign test on the overall average Waiting Factors of all of the tests and all of the stops, which are noted as:

$\mu 1$=the population mean of the Waiting Factors using pure flexible scheduling policy;

$\mu 2$=the population mean of the WF's using threshold policy;

$\mu 3$=the population mean of the WF's using rounded flexible scheduling.

A brief report on the result has been presented in the following table:

Table IV.4.7 Overall Effectiveness (Two Terminals, $\alpha=0.15$)

No.	Sample Mean (WF%)	Null Hypothesis Ho	P-value (Sign Test)	Decision
1	Pure Fle. Sch. = 134.4	$\mu 1 \geq \mu 2$	0.0002	Reject Ho
2	Threshold=135.6	$\mu 3 \geq \mu 2$	0.0000	Reject Ho
3	Rou. Fle. Sch.=131.9	$\mu 1 \geq \mu 3$	1.0000	Accept Ho

Table IV.4.8 Overall Effectiveness (Time Points, $\alpha=0.15$)

No.	Sample Mean (WF%)	Null Hypothesis Ho	P-value (Sign Test)	Decision
1	Pure Fle. Sch.=120.8	$\mu 1 \geq \mu 2$	0.0000	Reject Ho
2	Threshold=123.1	$\mu 3 \geq \mu 2$	0.0000	Reject Ho
3	Rou. Fle. Sch.=121.2	$\mu 1 \geq \mu 3$	0.0595	Reject Ho

From this sign test (which does not impose any particular requirement on the data distributions), we can see that on average, the two flexible scheduling policies have both shown to be more effective than threshold in reducing the WF's, and thus the average passenger waiting time along the route. The very small p-values for test No.1 and No.2 in both tables also show that the improvement is significant on average. The results from the test No.3 confirms our previous conclusion that rounded flexible scheduling policy only show an improvement in the service over the pure flexible scheduling when there are very few control points (which are the two terminals in our tests).

Compared to the threshold policy, which has been shown to be effective in improving the service with high-frequency service level, the effectiveness of the two flexible scheduling policies can be shown from the average time saved (in seconds) for the passengers waiting at the stops:

	Pure Fle. Sch. vs Threshold	Rounded Fle. Sch. vs Threshold
Two Terminals	1.08 seconds saved	3.35 seconds saved
Time Points	2.07 seconds saved	1.71 seconds saved

We would conclude that the improvement is significant because the passengers' usage on

Route 95 is very heavy. While the improvement in AWT is significant from a statistical point of view, it is probably not perceptible from the passengers' point of view. However, as much of the improvement is due to reduction in the headway variability, the most significant improvement for passengers is likely to be the reduced probability of waiting longer than the planned headway.

The two charts in the following two pages will illustrate the average WF's (for 40 tests) of all the 50 stops along the route. Since there are 50 stops along the route, we used line charts instead of bar charts to make the charts clearer (control stops have been marked). In the charts, we can see that:

•On average using more control points will improve the service. For two terminals the WF's are in the range of [117, 164], while for the time points the WF's are within a lower range from 116 to 135;

•At control points the WF's are decreased, while the further a stop parted from the control point, the higher the WF's is expected to be as the positive effect of the control point wears off.

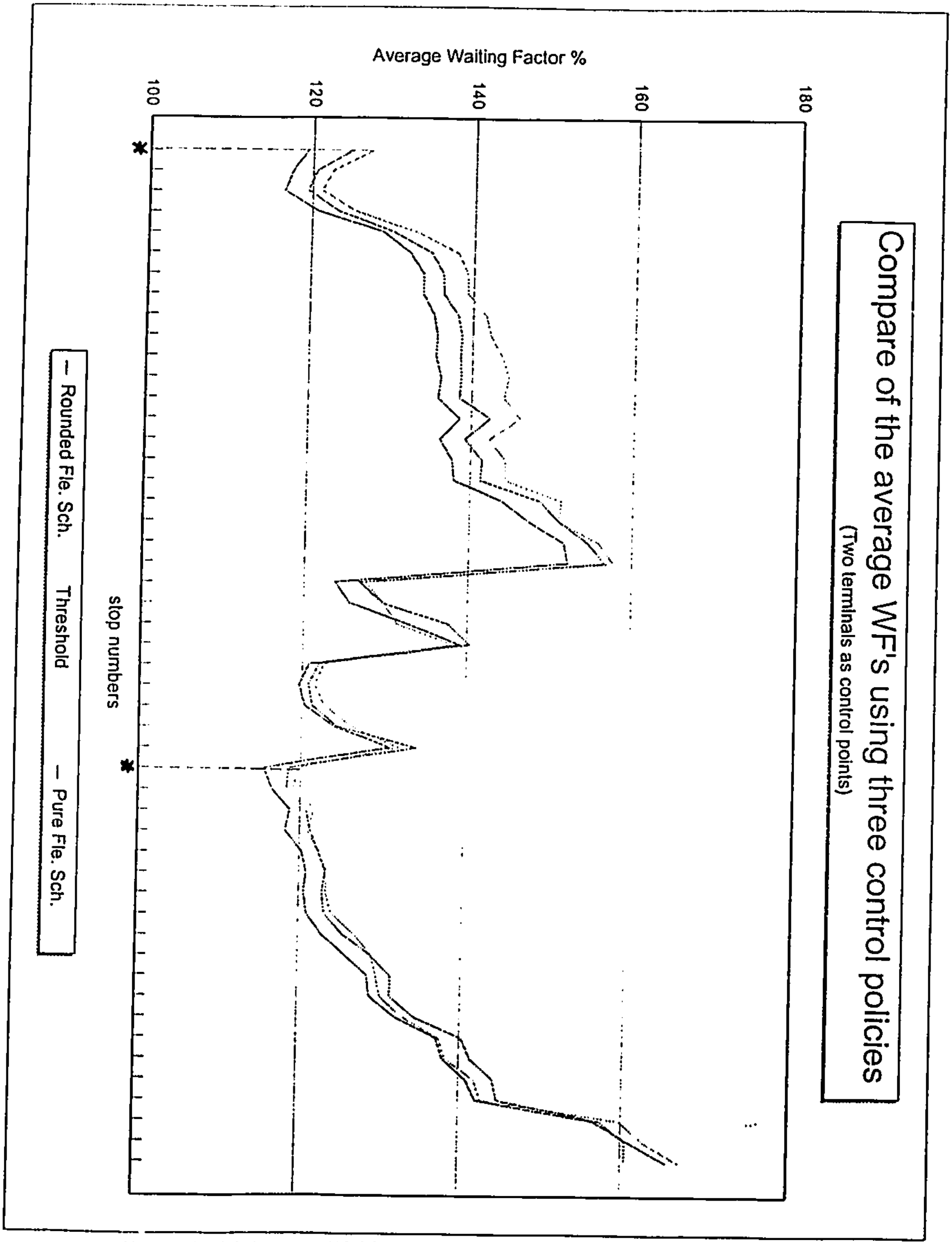


Figure IV.4.1 Average Waiting Factors for Two Terminals as Control Points

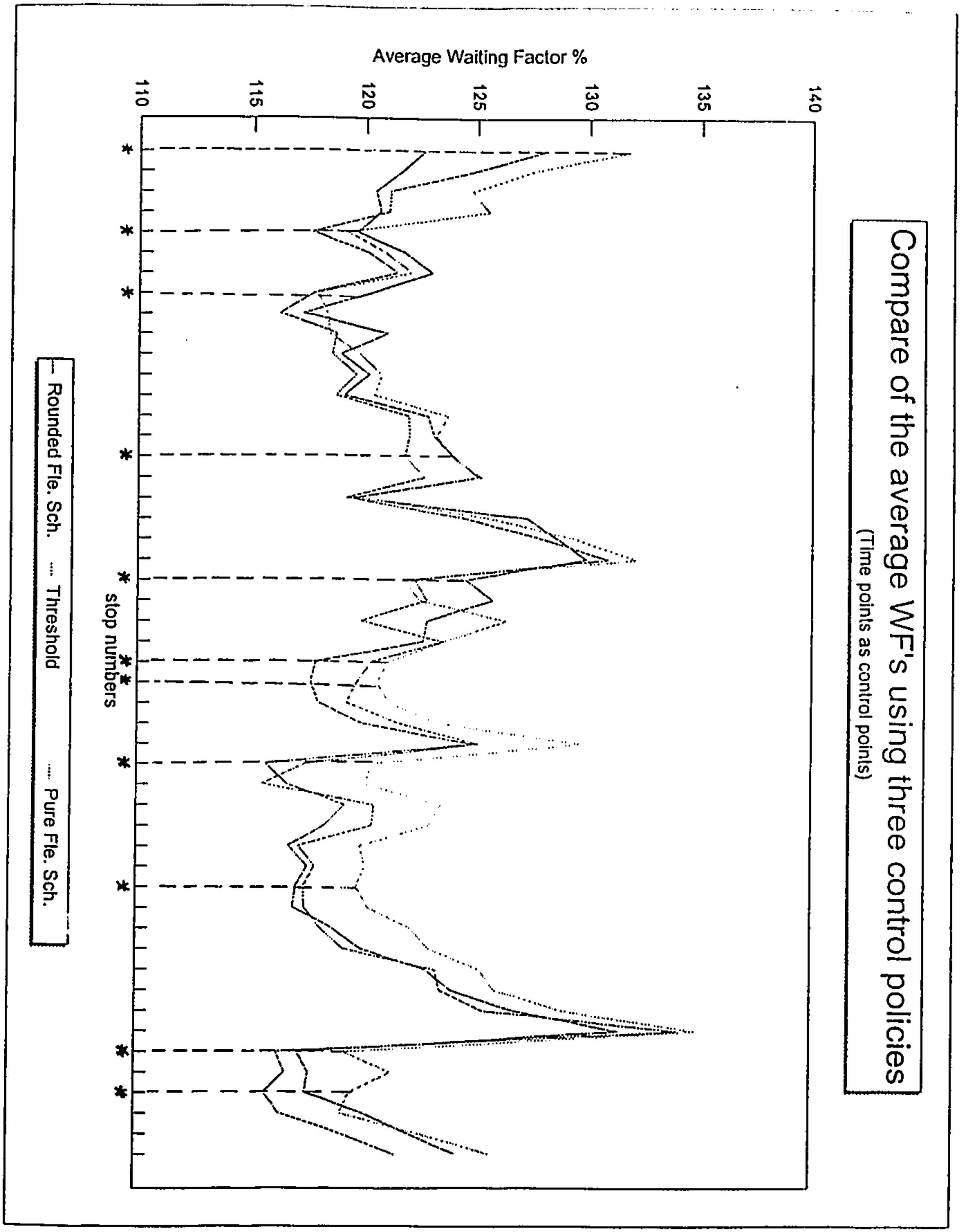


Figure IV.4.2 Average Waiting Factors for Time Points as Control Points

V. Development of User Interface

The ultimate goal of our research is to expand the existing control module into a knowledge-based system (KBS), which will be capable of analysing a given situation based on knowledge acquired by experience and experimentation, and choose the most appropriate control action(s) to rectify the situation and improve bus service reliability. Before this thesis work, there were two headway control policies available for testing purposes, namely the threshold policy and the message board policy. Now, flexible scheduling has been added into the control module as the third available headway control policy.

Some general definitions of knowledge-based systems can be found in [5].

In this chapter, we describe the development of a user-friendly interface allowing users to easily and conveniently use both the simulation model and the control module. The control module is not currently set up as a knowledge-based system capable of choosing from a set of available control policies the policy which is most appropriate for the situation at hand. However, the user may choose a particular control policy so that the control module will control the bus according to that policy whenever needed automatically. To do this, the user needs to type the proper commands manually, which is difficult to do for users who are not familiar with the UNIX operating system, or the source codes of the simulation model and of the control module. The user interface has been designed to allow any user to load the control policy of his or her choice in the control module through easy-to-use menus with this interface. It will also be easy for new control policies to be added to the user interface menus and eventually to get access to a real knowledge-based control system.

V.1 Requirements of the Development of the User Interface

There are at least two reasons for us to develop a user interface between the users and the simulation model and the control module as part of this thesis work. First, the simulation model was ported into the Sun SPARC ELC station running UNIX from its original version due to the requirements of both the memory space and the multi-processing capacity. Unfortunately, at this time, no user-friendly graphic user interface (GUI) had been designed to allow easy access to the simulation model and the control system, and all the operations related to the simulation and the control actions had to be done manually by the users using certain UNIX and Prolog commands. For example, in order to set up the simulation model, the user first needed to access the right directory, and then type in the name of the simulation model: hence, the user needed to know what was the program name and where the program was stored. It also meant that the user had to be familiar with the relation between the simulation model, the control module, as well as the UNIX operating system and the Prolog language in order to be able to operate the system. Given the fact that most of the users might not necessarily be familiar with all these systems, it was necessary to develop a user-friendly interface for the users to conduct the simulation experiments and use the control actions.

The second reason is to provide an efficient way of allowing the simulation model and the control module to exchange information without manual intervention by the user. As mentioned previously, the simulation model is a very large and complex program which is designed to simulate the movement of buses along a given route (OC Transpo Route 95 in this case). This includes dispatching buses from the various stops and simulating the entrance and exit of buses (blocks) from the system based on schedule data files. From a control point of view, the system is only capable of performing holding policies at user-specified control stops, based on either schedule adherence or headway adherence (the so-called threshold policy used in this thesis). In order to perform other more sophisticated control policies (such as the message board or flexible scheduling policies), two options are possible: to program these policies directly in the source code of the simulation model or to program these policies inside a control module which will dictate the control actions externally and communicate them to the simulation model. This communication may require changing some key parameters (for example, the dispatching headway in the flexible scheduling policy) or it may alter the contents of some files (for example, adding or deleting trips in the event tables).

We chose to use the second option, and thus not modifying the source code of the simulation model. It is much more difficult to include changes in the simulation model source code, and given the model makes use of a large number of subroutines, changing the source code may have unforseen and undesirable effects on the running of the simulation [5]. Furthermore, it is better to have the simulation model do what it was designed to do, that is simulating the movement of buses. Finally, by programming control policies in an external control module, it becomes much easier to modify the existing policies, to include new ones, and to eventually build a knowledge-based system. Given this choice, we needed to design a way to allow information exchange between the simulation model and the control module. Thus, we wanted users to be able to easily test the effectiveness of various control policies through a menu-driven user interface. The user should be able to view two windows: one which describes the running of the simulation and the other which reports on the actions of the control module, and these models needed to be able to communicate with each other.

To allow such control connections through communications among multi-processes, a system presented in the following figure which includes the following subsystems should be designed:

•**AVLC System** provides up-to-date block to bus assignments and schedules;

•**Simulation Model** simulates buses running on a given route, sends the simulated data about the current simulation and the existing problems (such as a bus breakdown) dynamically to the control module, and interrupts the simulation, waits for instructions from the control module, and then resumes as dictated by the control module. As we mentioned earlier, the simulation model was designed to be capable of updating its data files according to the changes of the AVLC system data files on a real-time basis. Yet the newest version of the simulation model is still as a standalone model at OC Transpo at present, and the data files for Route 95 used for our test are still the old ones which have not been updated to the current AVLC data;

•**Control Module** is designed to eventually become a knowledge-based system, which will be capable of performing suitable control actions on the simulation model by automatically modifying relevant **Running Files or Control Parameters** (e.g., the headway used for dispatching buses from control points in flexible scheduling) based on the current situation. At present, the control module is only capable of performing one control policy at a time, and needs to be initiated by the user who must choose the appropriate control policy through a user interface;

•**User Interface** which currently allows the users to activate the simulation model on a standalone basis, or with the control module. It also provides a better operating environment for the user: for example, it makes the storage of simulation reports easier. In further developments, and if needed by OC Transpo, through the user interface, the user will be able to run the simulation at a real-time speed and perform control actions manually, as would do a controller. This function would be most useful for training purposes;

•**Running Files** are data files that are relevant to the current simulated buses and to the control actions taken by the control module, including the relevant AVLC data and the data for communication between the simulation model and the control system. These **Running Files** can be updated according to AVLC data files or be rewritten by the control system to conduct a control action. Users can change only some of the parameters (i.e., those listed in the menus of the simulation model) prior to its running.

☞The development of the user interface is therefore essential.

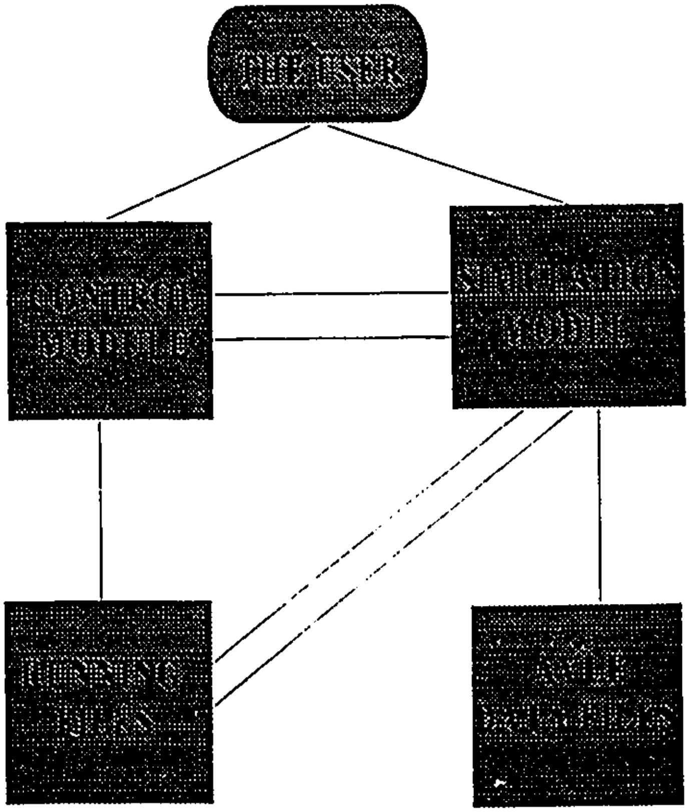


Figure V.1: COMPONENTS AND THEIR RELATIONSHIPS IN THE KBS OF BUS SERVICE CONTROL USING AVLC INFORMATION

V.2 Design of the User Interface

A ■ Purposes of the User Interface:

•To allow easy (user-friendly) access to both the simulation model and the control system:

•To facilitate hypothesis testing such as those related to the testing of the effectiveness of certain control policies;

•To allow new control policies to be easily incorporated into the control system.

We designed the user interface to be menu-driven. It was developed using shell programming under UNIX. Before we describe the menus and their functional accessibilities, we would like to address a fact existing in the current operating system, which makes the development of the user interface more difficult and more interesting.

Due to the updating of the file system in the Computer Science Department, the existing control system developed by Lule Chen cannot be compiled on other stations but the host station "csia" as of the summer of 1994, and this situation has not been changed since then. The advice from the consultant of Computer Science Department is "to compile the Prolog programmes on csia". As we mentioned before, there needs to be a communication between the simulation model and the control system: therefore, the simulation model must also run on csia because it has been developed to communicate with the control system on the same host station. So how can we get access to csia station?

The easiest way is to use the C-shell command "xon csia" to open a remote X-window on csia, and then work in that window (processes activated by this window will be carried on csia). Therefore, we need to open at least two windows on csia, one for the control system and one for the simulation model. Here we have to explain how the simulation model and the control system communicate, because this influences the order in which these two systems must be set up: the control module has to be set up before the simulation model starts. When it is activated, the simulation model will try to build up a connection with the control module by identifying its processid before the start of the main program of the simulation model: if the connection cannot be built up for any reason (e.g., the control module has not been set up yet), the simulation model will be terminated and a fatal error message will be given. During the running of the simulation model, it may pause its simulating to exchange information with the control module, and resume the simulating according to the instructions given by the control module. Therefore, the control module must be activated first in order to be ready to receive calls from the simulation model, and we have to make sure that this will always be the case when the user interface is used.

B■Description of the Menus:

☞*Main_Menu*:

```
***********************************************************
*                                                         *
*          Welcome to the User Interface for Bus          *
*                                                         *
*       Simulation  Model  and  the  Control Module       *
*                                                         *
*       Read_me.................................(r)       *
*                                                         *
*       start Simulation........................(s)       *
*                                                         *
*       start Control system....................(c)       *
*                                                         *
*       Move the results .......................(m)       *
*                                                         *
*       switch to Tools.........................(t)       *
*                                                         *
*       Quit....................................(q)       *
*                                                         *
```

•*Read_me*

This is a brief introduction to the user interface.

•*Start the simulation model*

This option will allow the user to get access to the original simulation model, as developed by CIGGT. The user will then access the menus of the simulation model.

•*Start the control module*

This option will allow the user to choose one of the control policies that are currently available in the control module, as given by the following sub-menu:

☞***Sub_menu A:***

```
*********************************************************
*              Available Control Policies               *
*                                                       *
*        full day Threshold.....................(t)     *
*                                                       *
*        Message board..........................(m)     *
*                                                       *
*        pure Flexible scheduling...............(f)     *
*                                                       *
*        Rounded flexible scheduling............(r)     *
```

After the user made his choice, the user interface will open three X-windows on "csia", and will:

①Start the control module in the first X-window capable of controlling the simulation model with the chosen control policy;

②Start the simulation model in the second X-window and set the simulation menu ready automatically for the users to make their options (for example, choose different control scenarios, change the running parameters, set the start and end time of the simulation and so on) before they start the running of the simulation;

③Open a third X-window on "csia" which allows the user to issue other commands not directly related to the user interface if need be;

④Replace the ***Sub_menu A*** by the main menu in the "login shell";

⑤Allow the communication between the simulation model and the control module during the running of the simulation model;

⑥Allow the user to stop the simulation model and the control module and turn off the X-windows on csia. To close the X-windows, the users just need to press [ctl_D] with the curser inside that window. After each running of the simulation, the output results are stored in an output file.

•Move the simulation results

This option will allow the user to store the simulation results in a new file before the next simulation overwrites the results. The simulation model does not have multiple running capacity, it cannot automatically run several consecutive experiments (with different random seeds) and store the results of the runs in separate files, one after the other, so the previous result reports will be overwritten when the simulation is started again. Therefore, it is very useful to have this option to allow easy storage of the results.

When the user chooses a control scenario in the simulation menu (i.e., no control scenario, schedule control scenario or headway control scenario), the results of the simulation will be stored in one of three output files, depending on which control scenario has been chosen. After the user chose to move the simulation results option, another sub-menu as shown below will appear which asks the user which of the three output files should be copied in a new file, the name of that new file, and where the new file should be kept (floppy disk or hard disk):

☞Sub_menu B

```
*************************************************************
*                                                           *
*       Options to move the results:                        *
*                                                           *
*       1........output report for No Control               *
*                                                           *
*       2........output report for Schedule Control         *
*                                                           *
*       3........output report for Headway  Control         *
*                                                           *
```

After one option has been chosen, the corresponding output files will be restored to a new file.

•Switch to tools

This option is a user-friendly interface for common operations in the UNIX operating environment, such as changing directories, managing files, etc. It is adapted from another project [30] for the users' convenience, and it has no effect on the simulation model and the control module.

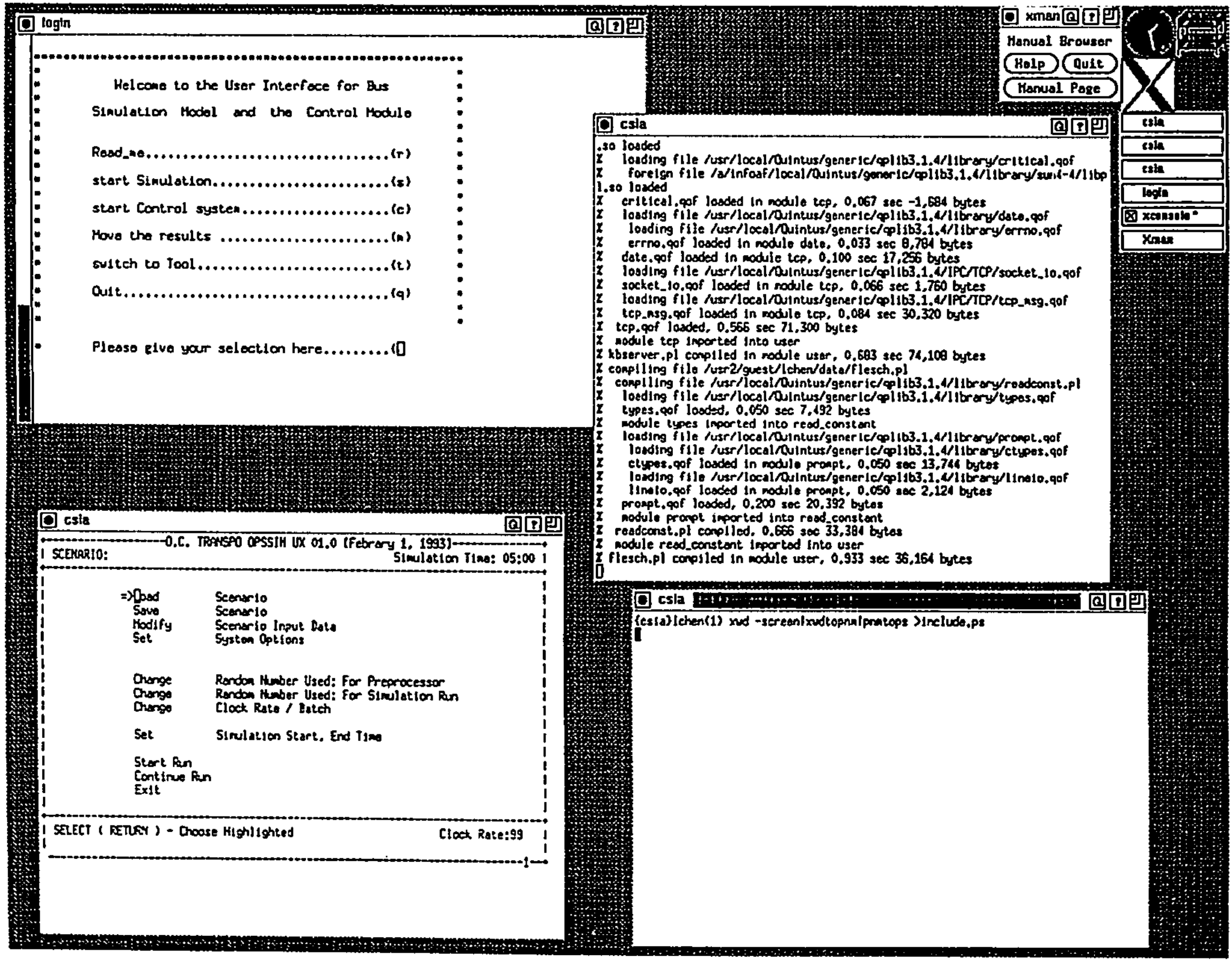
•Quit

This option will allow the user to leave the user interface; the system will ask for a confirmation and will remind the user to take his floppy disk before leaving the user interface.

At present, only the threshold and flexible scheduling policies are available (for some reasons, the message board module does not work properly). With this user interface, it is very easy to include other new policies which may be available in the future: it only requires adding an option in the ***Sub_menu A***, and adding an option accordingly in the main program for the user interface. This will be described in section V.3(D). Of course, the main difficulty lies in programming this new policy and making the necessary changes to the simulation source code to allow the two systems to communicate the relevant information.

C■Display of the User Interface

The following are two images of the user interface dumped from the Sun station screen with the "login shell" used to display the main menu and three X-windows on "csia" (one for simulation model, one for the control module and another for some other purposes such as monitoring the processes or dumping the images as described previously). After any option has been selected on ***Sub_menu A***, the user will need to position the three X-windows on the screen by moving the mouse and clicking a location where you wish the window to be opened by the system.



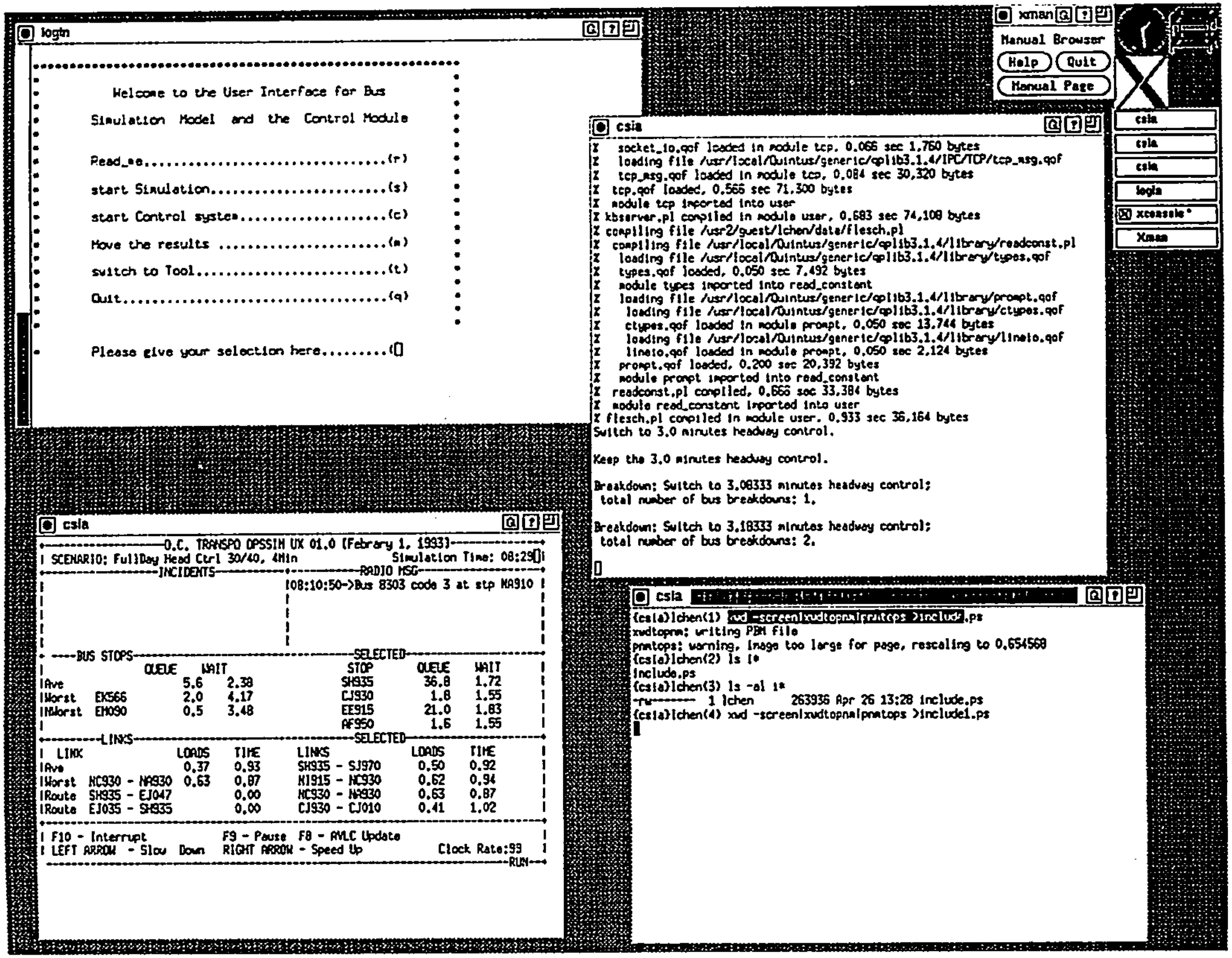
```
****************************************************************
*                                                              *
*       Welcome to the User Interface for Bus                  *
*     Simulation  Model  and  the  Control Module              *
*                                                              *
*     Read_me.................................(r)              *
*     start Simulation........................(s)              *
*     start Control system....................(c)              *
*     Move the results .......................(m)              *
*     switch to Tool..........................(t)              *
*     Quit....................................(q)              *
*                                                              *
*     Please give your selection here.........()
```

```
+----------------O.C. TRANSPO OPSSIM UX 01.0 (Febrary 1, 1993)--------------+
| SCENARIO:                                     Simulation Time: 05:00 |
+-------------------------------------------------------------------------+
|
|      =>Load       Scenario
|        Save       Scenario
|        Modify     Scenario Input Data
|        Set        System Options
|
|        Change     Random Number Used: For Preprocessor
|        Change     Random Number Used: For Simulation Run
|        Change     Clock Rate / Batch
|
|        Set        Simulation Start, End Time
|
|        Start Run
|        Continue Run
|        Exit
|
+-------------------------------------------------------------------------+
| SELECT ( RETURN ) - Choose Highlighted                   Clock Rate:99 |
+-------------------------------------------------------------------------+
```

```
.so loaded
%   loading file /usr/local/Quintus/generic/qplib3.1.4/library/critical.qof
%    foreign file /a/infoaf/local/Quintus/generic/qplib3.1.4/library/sun4-4/libp
l.so loaded
%   critical.qof loaded in module tcp, 0.067 sec -1,684 bytes
%   loading file /usr/local/Quintus/generic/qplib3.1.4/library/date.qof
%    loading file /usr/local/Quintus/generic/qplib3.1.4/library/errno.qof
%    errno.qof loaded in module date, 0.033 sec 8,784 bytes
%   date.qof loaded in module tcp, 0.100 sec 17,256 bytes
%   loading file /usr/local/Quintus/generic/qplib3.1.4/IPC/TCP/socket_io.qof
%   socket_io.qof loaded in module tcp, 0.066 sec 1,760 bytes
%   loading file /usr/local/Quintus/generic/qplib3.1.4/IPC/TCP/tcp_msg.qof
%   tcp_msg.qof loaded in module tcp, 0.084 sec 30,320 bytes
%  tcp.qof loaded, 0.566 sec 71,300 bytes
%  module tcp imported into user
% kbserver.pl compiled in module user, 0.683 sec 74,108 bytes
% compiling file /usr2/guest/lchen/data/flesch.pl
%  compiling file /usr/local/Quintus/generic/qplib3.1.4/library/readconst.pl
%   loading file /usr/local/Quintus/generic/qplib3.1.4/library/types.qof
%   types.qof loaded, 0.050 sec 7,492 bytes
%   module types imported into read_constant
%   loading file /usr/local/Quintus/generic/qplib3.1.4/library/prompt.qof
%    loading file /usr/local/Quintus/generic/qplib3.1.4/library/ctypes.qof
%    ctypes.qof loaded in module prompt, 0.050 sec 13,744 bytes
%    loading file /usr/local/Quintus/generic/qplib3.1.4/library/lineio.qof
%    lineio.qof loaded in module prompt, 0.050 sec 2,124 bytes
%   prompt.qof loaded, 0.200 sec 20,392 bytes
%   module prompt imported into read_constant
%  readconst.pl compiled, 0.666 sec 33,384 bytes
%  module read_constant imported into user
% flesch.pl compiled in module user, 0.933 sec 36,164 bytes
```

```
(csia)lchen(1) xwd -screen|xwdtopnm|pnmtops >include.ps
```

Figure V.2.1 Image of the user interface using pure flexible scheduling before the running of the simulation



```
Welcome to the User Interface for Bus
Simulation  Model  and  the  Control Module

Read_me..............................(r)
start Simulation.....................(s)
start Control system.................(c)
Move the results ....................(m)
switch to Tool.......................(t)
Quit.................................(q)

Please give your selection here.........()
```

```
X   socket_io.qof loaded in module tcp, 0.066 sec 1,760 bytes
X   loading file /usr/local/Quintus/generic/qplib3.1.4/IPC/TCP/tcp_msg.qof
X   tcp_msg.qof loaded in module tcp, 0.084 sec 30,320 bytes
X  tcp.qof loaded, 0.566 sec 71,300 bytes
X  module tcp imported into user
X kbserver.pl compiled in module user, 0.683 sec 74,108 bytes
X compiling file /usr2/guest/lchen/data/flesch.pl
X  compiling file /usr/local/Quintus/generic/qplib3.1.4/library/readconst.pl
X   loading file /usr/local/Quintus/generic/qplib3.1.4/library/types.qof
X   types.qof loaded, 0.050 sec 7,492 bytes
X   module types imported into read_constant
X   loading file /usr/local/Quintus/generic/qplib3.1.4/library/prompt.qof
X    loading file /usr/local/Quintus/generic/qplib3.1.4/library/ctypes.qof
X    ctypes.qof loaded in module prompt, 0.050 sec 13,744 bytes
X    loading file /usr/local/Quintus/generic/qplib3.1.4/library/lineio.qof
X    lineio.qof loaded in module prompt, 0.050 sec 2,124 bytes
X   prompt.qof loaded, 0.200 sec 20,392 bytes
X   module prompt imported into read_constant
X  readconst.pl compiled, 0.666 sec 33,384 bytes
X  module read_constant imported into user
X flesch.pl compiled in module user, 0.933 sec 36,164 bytes
Switch to 3.0 minutes headway control.

Keep the 3.0 minutes headway control.

Breakdown; Switch to 3.08333 minutes headway control;
 total number of bus breakdowns: 1.

Breakdown; Switch to 3.18333 minutes headway control;
 total number of bus breakdowns: 2.

[]
```

```
+------------------O.C. TRANSPO OPSSIM UX 01.0 (Febrary 1, 1993)--------------+
| SCENARIO: FullDay Head Ctrl 30/40, 4Min               Simulation Time: 08:29[]|
+-------------------INCIDENTS--------------+------------RADIO MSG--------------+
|                                          |08:10:50->Bus 8303 code 3 at stp NA910 |
|                                          |                                    |
|                                          |                                    |
|                                          |                                    |
|                                          |                                    |
+ ----BUS STOPS-----------------------------------SELECTED---------------------+
|                 QUEUE   WAIT                    STOP      QUEUE   WAIT       |
|Ave                5.6    2.38                   SH935      36.8    1.72       |
|Worst   EK566      2.0    4.17                   CJ930       1.8    1.55       |
|NWorst  EM090      0.5    3.48                   EE915      21.0    1.83       |
|                                                 AF950       1.6    1.55       |
+---------LINKS-----------------------------------SELECTED--------------------+
|  LINK                LOADS   TIME    LINKS              LOADS   TIME        |
|Ave                    0.37   0.93    SH935 - SJ970       0.50   0.92        |
|Worst  NC930 - NA930   0.63   0.87    NI915 - NC930       0.62   0.94        |
|Route  SH935 - EJ047          0.00    NC930 - NA930       0.63   0.87        |
|Route  EJ035 - SH935          0.00    CJ930 - CJ010       0.41   1.02        |
+-----------------------------------------------------------------------------+
| F10 - Interrupt             F9 - Pause  F8 - AVLC Update                    |
| LEFT ARROW  - Slow  Down    RIGHT ARROW - Speed Up           Clock Rate:99  |
+-----------------------------------------------------------------------RUN---+
```

```
(csia)lchen(1) xwd -screen|xwdtopnm|pnmtops >include.ps
xwdtopnm: writing PBM file
pnmtops: warning, image too large for page, rescaling to 0.654568
(csia)lchen(2) ls i*
include.ps
(csia)lchen(3) ls -al i*
-rw-------  1 lchen      263936 Apr 26 13:28 include.ps
(csia)lchen(4) xwd -screen|xwdtopnm|pnmtops >include1.ps
```

Figure V.2.2   Image of the user interface

using flexible scheduling during the running of the simulation

In *figure V.2.1*, the first X-window containing the control module was positioned at the top right of the screen, the second X-window showing the menu of the simulation model was positioned at the bottom left of the screen while the third general purpose X-window was positioned at the bottom right of the screen. It is from that window that we were able to dump the screen image to a file named "include.ps". The window on the top left of the screen is the "login shell" showing the user interface ***Main_Menu***.

Figure V.2.2 is the same screen setups during the running of the simulation model. In the control module window, general comments have been issued following the compilation report to inform the user of the current situation (such as number of bus breakdowns) and control actions taken (changes in the dispatching headway).

V.3 Design and Development of the User Interface

A ■ Use some instream data

As suggested in [10], instream data are those keyboard input data which cannot be separated from the command input stream of the shell. After Prolog has been called up, some keyboard input data will be needed to run the control module written in Prolog. These input data can be treated as instream data so that the Prolog command reads them as standard input. For example, the commands used to activate the flexible scheduling control module (starting Prolog, opening the programmes and running the programmes) which was named PROX2 are shown below:

```
cd $HOME/data                    #go to directory $HOME/data
prolog <<R_u_N                   #start Prolog and start of the instream data
[kbserver],[flexibleSHDL],go.    #open files and then run
R_u_N                            #end of the instream data
```

Whenever this PROX2 file is called up, it will execute the above actions. To illustrate how PROX2 works, please refer to the examples in the following page.

B ■ Call up X-windows in the main programme of the user interface

After one option has been chosen from ***Sub_menu A*** as shown before, the system automatically open three X-windows on csia using the command "xon csia" three times in the main programme of the user interface: the first window is for the control module, the second is for the simulation model, and the third is for any other purposes such as monitoring the processes or dumping the images. The logic of the user interface main programme will follow these steps:

①Keep a copy of the original ".cshrc" file, and replace it by a new one as will be discussed below;

②Open a file named "PROID0" (the name has no special meaning);

③Use "xon csia" three times to open three X-windows;

④Replace the current ".cshrc" file by the original one.

C■Use the ".cshrc" file to start programs in remote host "csia"

".cshrc" is the initial file used to setup both interactive and non-interactive C-shells, which are shells (command interpreter) with a C-like syntax and advanced interactive features. When the "xon" command is used to open a X-window on a remote host, the ".cshrc" file will be called to initiate the C-shell inside the X-window. We decided to put the commands needed to activate the simulation model and the control model in this ".cshrc" file, so that the two models will be activated automatically by this file right after the "xon csia"command has been used in the user interface main programme.

The commands added to the ".cshrc" file are only relevant to the user interface, and they should not affect the setup of any other C-shells. Hence, the ".cshrc" file will be changed only when needed (to open the three windows on "csia"and activate the control module and the simulation model), and then be replaced by the original ".cshrc" file immediately after. The modifications added to the original ".cshrc" file are reported below:

```
# additional setups for flexible scheduling policy-----------------------------------------------
if ( `hostname` == "csia" ) then              # if the host is "csia"
if (-f ~/PROID0) then
        mv ~/PROID0 ~/PROID1
        echo state1
else if (-f ~/PROID1) then
        mv ~/PROID1 ~/PROID2
        echo state2
        ~/thesis/PROX2                        #start the flexible scheduling control module
else if (-f ~/PROID2) then
        mv ~/PROID2 ~/PROID3
        echo state3
else if (-f ~/PROID3) then
        mv ~/PROID3 ~/PROID4
```

```
            echo state4
            cd ~/data
            sleep 10                               #make sure the control module be ready first
            fle                                    #start the simulation model
    else if (-f ~/PROID4) then
            mv ~/ PROID4 ~/ PROID5
            echo state 5
    endif
    endif
    #end------------------------------------------------------------------------------------------
```

The purpose of these commands is to open a X-window and activate a program in it: normally, "xon csia" sets up C-shell on host "csia" but nothing is activated, and the user would need to activate the programs manually. We added the above commands to the ".cshrc" so as to be able to activate the control module and the simulation model automatically.

As there are two programs that need to be activated, we design the "if" statements so that the control module is activated in the first X-window right after it is opened, the simulation model is activated in the second window right after it is opened, and nothing is activated automatically after the C-shell is setup in the third X-window. The "sleep 10" command is used to make sure that the simulation model will not be called up before the control model is setup.

Such a modification to the ".cshrc" file is created for all control policies available on Sub_menu A. Only two command lines are dependent of the control policy: those appear in bold. The first one calls for the execution of PROX2 which is the control module code for the pure flexible scheduling policy: if another control policy is used, PROX2 should be replaced by the appropriate executable file name. The second calls for the execution of the simulation model designed to communicate with the Prolog control module running the pure flexible scheduling policy: if another policy is used, "fle" must be replaced accordingly. The rest of the modification to the ".cshrc" file is the same for any other control policy. This may take more memory space, but it makes things easier for including new control policies into the user interface.

D■Add new control policies into the user interface

In order to add new control policies into the user interface in the future, these easy-to-follow steps will be needed:

①Add the option with the name of the policy associated with a letter that has not been used in ***Sub_menu A*** by adding an extra option in a file named "menu" (under subdirectory "thesis") in which all the menus are stored. To do this, simply change directory to "thesis" by using "cd ~/thesis", and then use "vi menu" to edit the "menu" file. After the edition is finished, save the changes and close the file by using "wq" in the vi command line;

②Add a new paragraph in the main programme of the user interface which can be called up by the new option in the ***Sub_menu A***. This new paragraph will be similar to the paragraphs associated with other existing options except that it will possess a different programme name associated to the new control policy. This can be explained by comparing the paragraphs for the threshold and the pure flexible scheduling policies in the main programme of the user interface as shown below (the statements in bold are the only statements that differ from policy to policy):

```
t|T) #use threshold control policy
        cp $path2/.cshrc.thr $HOME/.cshrc
        date > $HOME/PROID0
        cd
        xon csia
        xon csia
        xon csia
        cp cshrc .cshrc
        rm PROID5
        cd $path2
        ;;
```

```
f|F)#use pure flexible scheduling policy
        cp $path2/.cshrc.fle $HOME/.cshrc
        data > $HOME/PROID0
        cd
        xon csia
        xon csia
        xon csia
        cp cshrc .cshrc
        rm PROID5
        cd $path2
        ;;
```

These two paragraphs are currently under one switch which is controlled by the option given through the ***Sub_menu A***.

③Add a new ".cshrc" (such as ".cshrc.thr" and ".cshrc.fle") file associated to the new control policy with only changes in some programme names in the file, such as using PROX3 instead of PROX2 to activate the new control policy after the option has been chosen.

E■Advantages and disadvantages of the user interface

The advantage of the user interface is that the operating environment has been improved. It is more user-friendly for the user, especially someone who is not familiar with the system. The user interface includes all the existing control policies and allows the user to make a choice among them, which makes the comparison between different control policies easier.

The problem with the user interface is that for someone who is very familiar with the operating environment and the control modules, it may not be as fast and as flexible as manual operation. This is because in order to make sure the simulation model will always be started after the control module has been activated, we simply let the process pause for 10 seconds before the simulation model is activated, which could slow the operation for someone who is very familiar with the entire system.

Overall the user interface is useful for the users, especially for new users.

V.4 A Brief User Guide for the User Interface

The following user guide is provided for the benefit of new users who are not familiar with the user interface or the UNIX Operating Systems:

•Login the system by providing the correct userid and password;

•Activate the user interface: type "start" in the "login shell", and the ***Main_Menu*** of the user interface will appear in the same shell;

•Choose one of the available options from the ***Main_Menu***: for example, choose "c" to access ***Sub_menu A*** in this "login shell";

•Choose option "f" from Sub_menu A. The user then will notice three X-windows will be called up one after the other; and finally the ***Sub_menu A*** in the "login shell" will be replaced by the ***Main_Menu*** again;

•Position the three appearing windows on the screen so that they can all be seen clearly (as shown in the images of the screen) of ***figure V.2.1***;

•Move the curser to the second X-window where the simulation menu is available; set the simulation options through this menu by following the steps needed as discussed in [6], and then start running the simulation model. The information similar to that shown in ***figure V.2.2*** will then appear on the first and the second window. Leave the curser in the simulation model during the running of the simulation to be able to interrupt and resume the simulation if needed;

•After the simulation is finished, choose the "Exit" option from the menu of the simulation model to terminate the simulation model. Press [ctl_D] to close the second X-window;

•Move the curser to the control model window, press [ctl_D] to stop the keyboard input required by the Prolog command, and then again press [ctl_D] to close this X-window;

•Move the curser to the general purpose X-window, use command "ps ux" to make sure there is no unwanted process left running on "csia", and then press [ctl_D] to close this X-window;

•Move the curser to the "login shell". Choose "m" from the ***Main_Menu*** to access ***Sub_menu B***. Choose the appropriate output report (associated with the control scenario used in the simulation), and give a new name for the file to which the chosen output report will be stored. This "move" can be done as soon as the simulation running is complete, and the user does not have to close the three X-windows before moving the output report;

•After the chosen output report has been saved, the Main_Menu will reappear in the "login shell" to allow the user to do another simulation or to leave the user interface;

Note that if the user wants to run the same control policy with different random seeds (or other parameters) in the simulation model, this can be done by simply making the necessary changes in the simulation menu and running the simulation again. It is advised to move the results of the previous run to another file before the rerunning of the simulation. However, if the user wants to test out another control policy, the three X-windows must be closed (as described above using [ctl_D]) and option "c" from the ***Main_Menu*** must be chosen.

•If the "Quit" option is chosen, then, after a confirmation is given, the user will be able to leave the user interface. Please remember to take your floppy disk if there is one;

•In order to logout from the system, use the "logout"command in the "login shell".

VI. Conclusion and Future Research

VI.1 Summary of the Results

Through this thesis research, we have developed and tested an improved headway control policy - flexible scheduling. This method was developed to handle the changes in the number of available resources (i.e., buses) on a given high-frequency service route which may be due to bus breakdowns for example. The idea is to recalculate the smallest achievable headway based on the current resources, and to use it for dispatching buses from the control points. Equations have been given for the calculations.

Simulation experiments using two terminals, and using the time points as control points have been performed and analysed where flexible scheduling was compared to the threshold policy, and the results have shown the effectiveness of flexible scheduling in better maintaining the planned service level when some bus breakdowns occur in the system.

Based on these results, we consider flexible scheduling as a very promising and useful headway control policy.

VI.2 Some Implementation Issues

In order to implement the flexible scheduling into a real transit system, some issues which may have an impact on implementation should be studied carefully. While a brief discussion follows, more research needs to be done to address these implementation issues.

■ **Costs**

•***Equipment***

In addition to the AVLC system which allows controllers to know when buses reach stops equipped with a detector, implementation of a headway control policy, and in particular of the flexible scheduling policy, will require some investment in equipment and technology.

In particular, software such as the control module used in this thesis is needed to implement headway control policies as too many decisions and actions must be taken on-line for a human controller to perform. This is even more true if several control points are used. The system must compute how long each bus must be held at each control stop, react to the changing number of available buses, and efficiently communicate control actions to the bus operators on-line.

In order to support such communication between the control system and the bus drivers, various alternatives can be considered. First, it may be possible to install on-board screens and communicate the control actions using the cellular phone or the electronic "beeper" technology: the drivers could read on the screen the holding messages for example. Clearly such system would be costly to install, but it would allow more immediate communication than if a human controller contacted drivers by radio. A second alternative would require the use of some clock at the control points, which would be used to provide information to both the drivers and the passengers. Much like the schedule information systems currently in use at major transfer points (such as at Hurdman station and Place D'Oleans), the clock would indicate when the next bus will depart, but based on real-time information, not on schedule information. The drivers would then coordinate their departure with this clock. This technology would probably be less costly, at least from the hardware point of view (no need for on-board screens in particular), and it would serve two useful purposes: allow on-line dispatching and control of buses and serve for public information.

•Labour Cost

As explained before, in our experiments we focused on one aspect of service reliability, namely the Average Waiting Time or the Waiting Factor, which allows us to evaluate the control policy from the passenger's point of view: for the passenger, a shorter average waiting time at the stop indicates a better service. The application of holding policies such as flexible scheduling may have an impact on labour cost, which the simulation model does not allow us to analyse at present. When flexible scheduling policy is used, the flexibility in the working time will be considered from the driver's point of view: how much longer or shorter than his booked shift time does the driver have to work due to the changes of the dispatching headway? This issue is very important to the drivers and to the transit agency, because it will bring up some labour cost concerns. More specifically, if a bus breaks down and the dispatching headway increases, some buses must be held back significantly at the control point, so that when his shift ends, he may not be able to finish his current trip or he may be required to do an extra trip. This is a very interesting research project for the future. However, with a good management system, hopefully there will be some ways to implement flexible scheduling into the real system without many extra labour cost.

Using flexible scheduling, the schedules and headway should not be rounded up into integer "minute" as is current practice at OC Transpo: this may save some labour costs, even if the rounded flexible scheduling is implemented instead of the pure flexible scheduling.

■The Advantages and Disadvantages of the Rounded Flexible Scheduling

•Advantages

First, rounded flexible scheduling is easy to implement because by rounding to the nearest 30 seconds, it will reduce the number of times the dispatching headway needs to be changed, and it is more akin to the traditional way which always round up every time piece to the integer minutes: it is easier for management and for the drivers to follow.

Simulation tests have shown that with very few control points, such as the two terminals, rounded flexible scheduling will build some slack (at the terminal, a longer recovery time may be provided) in the system, which has been shown to be a very good method to deal with the problems of headway adherence associated with bus breakdown problems. Although the real bus breakdown probability is much lower than the one we used in our simulation experimentation, it has been confirmed that the bus breakdown (including buses totally out of order and buses reported by the drivers as not safe for operation) is a major problem in the transit system at OC Transpo.

Considering the equipment costs and the effectiveness of the control policy, it seems preferable to implement rounded flexible scheduling using the two terminals as the control points, so that the dispatching headway is only changed at two terminals. Also, the additional layover is added at the terminals as opposed to a stop along the route so that no passenger is kept waiting for long period of time inside the bus at any stop on the given route.

•Disadvantages

For a better service control through more control points, the effectiveness of rounded flexible scheduling compared to pure flexible scheduling will be reduced due to the fact that it will hold the buses unnecessarily longer than it needs to. This can be explained by a simple example. If the planned headway is 3 minutes, and due to a bus breakdown, the h(a) is now 3.05 minutes. By using rounded flexible scheduling, 3.5 minutes will be used to control the dispatching of buses at all the control points immediately after the bus breakdown occurred. Given any control points besides the terminals, after the dispatching headway changes, the first bus to arrive at the control point will be held 0.45

minutes more than needed, the second will be held 0.9 minutes more, and so on. This extra holding will for sure have an impact on those passengers on the bus: they have to wait longer than if pure flexible scheduling policy or threshold policy had been used; it will also reduce the effectiveness of flexible scheduling: it was shown in our experimentation that when time points were the control points, rounded flexible scheduling policy was not as effective as pure flexible scheduling in improving the service. To follow up the above discussion, it is important, in the implement of either the pure or the rounded flexible scheduling policies, to start dispatching buses with the new h(d) from the terminals first, and then implement h(d) at the other control points only as soon as the first bus to be dispatched from a terminal with the new h(d) reaches that control point. If this is not done, the implementation of flexible scheduling with many control points will have the undesirable negative impact of imposing increasingly longer holding delays at the control stops during the transition period, rather than absorbing these delays as recovery time at the terminals which would not affect passengers.

■Public Information

We have discussed the issue of what is the appropriate information that should be made known to the public. Flexible scheduling is a headway control policy. It may probably bring in changes in the dispatching headway at the chosen control points, which will eventually change the operating situation on the whole route. As the major service disruptions (bus breakdowns and drivers not showing up) are usually not predictable, the application of flexible scheduling may change from time to time and from situation to situation. This implies that the information made known to the public should not be fixed for the period of high-frequency service so that a better match between the control policy (which may deviate the service from the schedules) and passenger behaviour will be achieved. Details about the changes in the public information are studied in section III.1.

■Location of Detectors and Other Issues

No particular requirement will be associated with the implementation of flexible scheduling, although some extra work for the controllers may be needed. But with the equipment as we suggested, and its dynamic connection with the AVLC system, this extra work could be taken by the computers.

IV.3 Future Research

Interesting issues in future research associated with flexible scheduling include:

•Expanding and testing the flexible scheduling to other period of the day, such as morning and afternoon off-peak period on Route 95 which provide a relatively high-frequency service (5 minutes planned headway), to study the suitability of flexible scheduling for those time periods;

•Testing the flexible scheduling on the schedule files currently used at OC Transpo in the real system, when they are available;

•Testing the correlation between the effectiveness of flexible scheduling and the time and the number of bus breakdowns. In our tests, only a brief explanation has been given to show that the total number of bus breakdowns should not have an undesirable impact on our analyses and results. More detailed research will help to identify the real impact from the bus breakdowns when flexible scheduling headway control policies are used;

•Evaluating the average time in the system for passenger, by taking into account the waiting time of the passengers already on the buses;

•Predicting the amount of extra labour costs (if there are any) when flexible scheduling is applied;

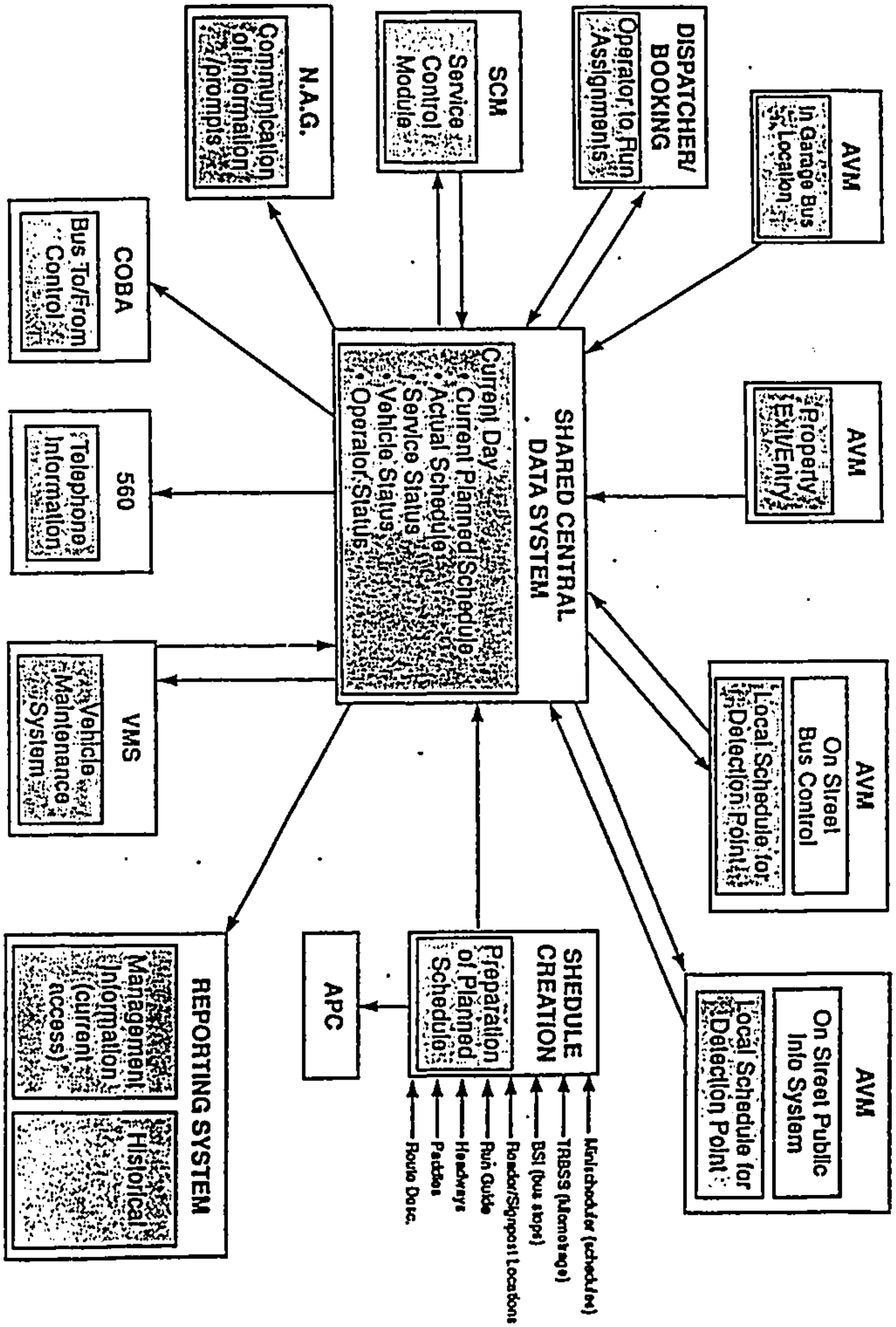
•Modifying the simulation so that it will always send the appropriate information and will alway resume its running according to what it has been instructed to do by the control module. More functions may need to be developed to make more statistical analyses possible: for example, a function may be needed for calculating the passenger waiting time on the bus, the standard deviation of headway at each stop, and so on;

•Service control and labour cost management during the transition period (for example, when the service changes from one level to another while some buses leave or enter the system);

•Developing more control policies into the control module and building up the knowledge-based system. More knowledge and understanding of the transit system must be acquired, the best situation for applying a given control policy must be identified, and the programming of more control actions will all contribute in moving the research toward the goal - to develop a knowledge-based system which can make the best control decision dynamically for any given problem in the transit system!

VII. Appendix

VII.1 AVLC Modular Concept at OC Transpo



VII.2 Public Schedule for Route 95 at OC Transpo

Route/Circuit

95

This schedule is effective Sunday September 4, 1994. Summer schedules are introduced each year in late June. A reduced service operates on holidays and selected days at Christmas.

Cet horaire est en vigueur à compter du dimanche, 4 septembre, 1994. Chaque année, à la fin de juin, les horaires d'été sont présentés. Un service réduit sera en vigueur lors des jours fériés et certains jours à Noël.

ROUTE AND SCHEDULE INFORMATION / INFORMATION - CIRCUIT ET HORAIRE : 741-4390
TDD / ATME : 741-5280 — CUSTOMER SERVICE À LA CLIENTELE : 748-4408

95 Blair & Orléans — eastbound / vers l'est

MONDAY TO FRIDAY / LUNDI À VENDREDI

from/de → to/vers

Baseline	Lebreton	Mackenzie King	Hurdman	Blair	Place d'Orléans
4:37	4:50	4:58	5:04	5:18	5:29
4:52	5:05	5:13	5:19	5:33	5:44
5:07	5:20	5:28	5:34	5:48	5:59
5:22	5:35	5:43	5:49	6:03	6:14
5:37	5:50	5:58	6:04	6:18	6:29
5:52	6:05	6:13	6:19	6:33	6:44
6:08	6:21	6:29	6:34	6:41	6:57
6:18	6:31	6:39	6:44	6:51	7:07
6:24	6:37	6:45	6:50	6:57	7:13
6:27	6:40	6:48	6:53	7:00	
6:31	6:45	6:55	6:59	7:06	7:22
6:35	6:49	6:59	7:03	7:10	
6:39	6:53	7:03	7:07	7:14	7:30

Buses run every 3, 4 or 5 minutes during the day to Blair, and every 2nd Bus ends at Place d'Orléans.

Les autobus circulent à chaque 3 ou 4 ou 5 minutes durant la journée jusqu'à Blair; chaque deuxième autobus termine son trajet à la Place d'Orléans.

Baseline	Lebreton	Mackenzie King	Hurdman	Blair	Place d'Orléans
18:20	18:34	18:42	18:51	18:58	
18:24	18:38	18:49	18:55	19:02	19:17
18:28	18:42	18:51	18:58	19:05	
18:32	18:46	18:54	19:01	19:08	19:23
18:37	18:50	18:58	19:04	19:12	19:25
18:43	18:56	19:04	19:10	19:17	19:29
18:49	19:02	19:10	19:15	19:22	19:34
18:55	19:08	19:16	19:21	19:28	19:40
19:02	19:15	19:23	19:28	19:35	19:47
19:12	19:25	19:33	19:38	19:45	19:57

then every 10 minutes until: / et chaque 10 minutes jusqu'à :

Baseline	Lebreton	Mackenzie King	Hurdman	Blair	Place d'Orléans
21:52	22:05	22:13	22:18	22:25	22:37
22:02	22:15	22:23	22:28	22:35	22:47
22:17	22:30	22:38	22:43	22:50	23:02
22:32	22:45	22:53	22:58	23:05	23:17

then every 15 minutes until: / et chaque 15 minutes jusqu'à :

Baseline	Lebreton	Mackenzie King	Hurdman	Blair	Place d'Orléans
0:17	0:30	0:38	0:43	0:50	1:02
0:32	0:45	0:53	0:58	1:05	1:17

95 Baseline — westbound / vers l'ouest

from/de → to/vers

Place d'Orléans	Blair	Hurdman	Mackenzie King	Lebreton	Baseline
4:11	4:21	4:35	4:40	4:50	5:03
4:26	4:36	4:50	4:55	5:05	5:18
4:41	4:51	5:05	5:10	5:20	5:33
4:56	5:06	5:20	5:25	5:35	5:48
5:11	5:21	5:35	5:40	5:50	6:03
5:26	5:36	5:50	5:55	6:05	6:18
5:41	5:51	6:05	6:10	6:20	6:33
5:51	6:05	6:12	6:17	6:25	6:39
6:06	6:20	6:27	6:32	6:40	6:54
6:16	6:30	6:37	6:42	6:52	7:07
	6:35	6:42	6:47	6:57	7:12
6:26	6:40	6:47	6:52	7:02	7:17
	6:44	6:51	6:56	7:06	7:21

Buses run every 4 or 5 or 6 minutes during the day, and every 2nd bus starts at Place d'Orléans.

Les autobus circulent à chaque 4 ou 5 ou 6 minutes durant la journée; chaque deuxième autobus débute son trajet à la Place d'Orléans.

Place d'Orléans	Blair	Hurdman	Mackenzie King	Lebreton	Baseline
18:21	18:33	18:40	18:45	18:56	19:11
	18:37	18:44	18:49	19:00	19:15
18:29	18:41	18:48	18:53	19:04	19:19
18:36	18:45	18:52	18:57	19:08	19:25
18:41	18:53	19:00	19:05	19:13	19:28
18:48	19:00	19:07	19:12	19:20	19:35
18:56	19:08	19:15	19:20	19:28	19:43
19:03	19:15	19:22	19:27	19:35	19:50
19:10	19:22	19:29	19:34	19:42	19:57
19:19	19:31	19:38	19:43	19:51	20:06
19:29	19:41	19:48	19:53	20:01	20:16

then every 10 minutes until: / et chaque 10 minutes jusqu'à :

Place d'Orléans	Blair	Hurdman	Mackenzie King	Lebreton	Baseline
21:49	22:01	22:08	22:13	22:21	22:36
21:59	22:11	22:18	22:23	22:31	22:46
22:14	22:26	22:33	22:38	22:46	23:01

then every 15 minutes until: / et chaque 15 minutes jusqu'à :

Place d'Orléans	Blair	Hurdman	Mackenzie King	Lebreton	Baseline
23:59	0:11	0:18	0:23	0:31	0:44
0:14	0:26	0:33	0:38	0:46	0:59

VII.3 The questionnaire format for survey I (*SET 1*)*

Purpose: To identify the MAXIMUM HEADWAY such that the headway control strategies should still be used to control bus service

QUESTIONS	**ANSWERS** (For 20 passengers)
1. Which bus are you waiting for? *(Answers are the bus numbers)*	☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐
2. How long have you been waiting? *(Answers are number in minutes)*	☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐
3. In how much time do you expect your bus to come? *(Answers are number in minutes)*	☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐
4. Assuming the time between two successive buses is 3 minutes, would you like to know the exact scheduled departure time of the bus? How about 5 minutes? 7 minutes? 10 minutes? 15 minutes? 20 minutes? 30 minutes?	☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐ *(Answers are the first numbers passenger chooses YES)*
5. Assuming you know the scheduled time of your bus, how long before that time would you usually arrive to the bus stop?	☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐ *(Answers are number in minutes)*

* ***In this survey I, question No. 4 was asked in an increasing headway order.***
Set 1 was defined as the group who were asked question No.4 in an increasing headway order

VII.4 The questionnaire format survey II (SET 2)**

Purpose: same as indicated in survey I.

<u>QUESTIONS</u>	<u>ANSWERS</u> (For 20 passengers)
1. Which bus are you waiting for? *(Answers are the bus numbers)*	☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐
2. How long have you been waiting? *(Answers are number in minutes)*	☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐
3. In how much time do you expect your bus to come? *(Answers are number in minutes)*	☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐
4. Assuming the time between two successive buses is 30 minutes, would you like to know the exact scheduled departure time of the bus? How about 20 minutes? 15 minutes? 10 minutes? *(Answers are the first numbers the passengers choose NO)* **7 minutes? 5 minutes? 3 minutes?**	☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐
5. Assuming you know the scheduled time of your bus, how long before that time would you usually arrive to the bus stop?	☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐ *(Answers are number in minutes)*

** *In this survey, question No. 4 was asked in a decreasing headway order*
Set 2 was defined as the group who were asked question 4 in a decreasing headway order

VII.5 The questionnaire format for the FINAL SURVEY

PURPOSE: TO identify the MAXIMUM HEADWAY such that the headway control strategies should still be used to control the bus service.

<u>QUESTIONS</u>	<u>ANSWERS</u> (For 45 passengers)
1. Which bus are you waiting for? *(Answers are the bus numbers)*	☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐
2. How long have you been waiting? *(Answers are number in minutes)*	☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐
3. In how much time do you expect your bus to come? *(Answers are number in minutes)*	☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐
4. Assuming the time between two successive buses is 30 minutes, would you like to know the exact scheduled departure time of the bus? How about 3 minutes? What is the largest time interval for which you would not need to know the scheduled departure time before heading to the bus stop?	☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ *(Answers are number in minutes)*
5.Assuming you know the scheduled time of your bus, how long before that time would you usually arrive to the bus stop?	☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ *(Answers are number in minutes)*

VII.6 Stops on Route 95 in the simulation model

Stop No	Stop Code	Stop Name
1*	SH935	BASELINE/STATION* (on both directions)
2	SJ970	TRANSITWAY/IRIS
3	SJ920	QUEENSWAY/STATION
4	NI915	LINCOLN FIELDS/STATION
5*	NC930	WESTBORO STATION*
6	NA930	TUNNEYS STATION
7	CJ920	OFF ON REQUEST
8*	CJ930	LEBRETON/STATION*
9	CJ010	SLATER/EMPRESS
10	CA940	SLATER/BAY
11	CA950	SLATER/KENT
12	CB960	SLATER/BANK
13	CB970	SLATER/METCALFE
14	CD900	MAC BRIDGE
15	CD955	LAURIER STATION
16*	CD975	CAMPUS STATION*
17	CE920	LEES STATION
18	AF910	HURDMAN/STATION
19	AE910	TRANSITWAY/TRAIN
20	EB915	AT LAU/S.C.
21	EC910	CYRVILLE STATION
22*	EE905	BLAIR STATION*
23	EK566	QUEENSWAY/JEANNE D'ARC
24	EM020	PROM.PLACE D'ORLEANS/CENTRUM
25	EM090	ST.JOSEPH/DUFORD
26*	EJ035	PLACE D ORLEANS*
27*	EM010	PROM.PLACED'ORLEANS/CENTRUM*
28	EM015	HWY XVII/CHAMPLAIN
29	EK564	QUEENSWAY JEANNE D ARC
30	EG001	BUSWAY/MONTREAL RD.
31*	EE915	BLAIR STATION*
32	EC900	CYRVILLE STATION
33	EB905	ST LAU S/C
34	AE900	TRANSITWAY/TRAIN
35	AF950	HURDMAN/STATION
36	CE940	LEES STATION
37*	CD985	CAMPUS/STATION*
38	CD965	LAURIER STATION
39	CD915	MAC BRIDGE
40	CB900	ALBERT/METCALFE
41	CB910	ALBERT/BANK
42	CA920	ALBERT/KENT
43	CA930	ALBERT/BAY
44	CJ020	TRANSITWAY ALBERT
45*	CJ900	LEBRETON STATION*
46	NA910	TUNNEYS STATION
47*	NC910	WESTBORO STATION*
48	NI910	LINCOLN FIELDS STATION
49	SJ900	QUEENSWAY/STATION
50	SJ960	TRANSITWAY/IRIS

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