VEHICLE AND CREW SCHEDULING: THE GENERAL PROBLEM AND A CASE STUDY OF THE MBTA

by

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ABSTRACT

Researchers have been looking for efficient and effective algorithms and models to solve a wide range of transportation scheduling problems over at least the last three decades. Many of these algorithms and models have been applied to scheduling problems in the real world with success. However, the complexity of these problems, the variety of constraints and the problem size remain critical challenges in scheduling problems.

This thesis discusses the general scheduling problem and desirable algorithms, and models for specific vehicle and crew scheduling problems for urban public transportation systems. Several computer-based scheduling systems have been developed and employed in urban public transportation systems in the last twenty-five years. The evolution of these systems is described showing that most of the newly developed or revised computer-based scheduling systems employ the concept of an "*interactive environment*" to make the systems more flexible and acceptable for different authorities.

The thesis then assesses the impacts and potential of one such computer-based scheduling tool in the MBTA context. The evaluations show that the installation of this scheduling system has helped to increase the MBTA schedule department productivity greatly even though not all its capabilities are yet being used. More scheduling efficiency and more important information (reports) are also available from the use of the computer-aided scheduling system. The following evaluations showed that the computer system is indeed able to produce feasible automated crew schedules for both small and large garages in the MBTA system, but it is much more difficult to find an acceptable automated crew schedule for the large garage because its optimized schedule is very sensitive to parameter settings.

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Chapter 1: Introduction

Efficient and effective algorithms and models have been widely studied and applied to transportation scheduling problems in different areas over the last three decades. The variety of constraints and the large problem size result in the complexity of scheduling problems. As a result, the implementation of these algorithms in computer system to deal with scheduling problems in the real word has become necessary and inevitable for transit authorities. Computer-aided transit scheduling systems were first developed and applied in North America and England in the 1970's. Until now, the importance and the benefits of the computer-aided scheduling system have been well learned for most transit authorities. To have a clearer understanding of the possible impacts and benefits that computer-aided scheduling systems can have on transit authorities, this thesis performs a detailed evaluation in the Massachusetts Bay Transportation Authority (MBTA) context. The HASTUS system, which is one of the most widely implemented computer-aided transit scheduling systems, is developed by the Transportation Research Center of the University of Montreal and GIRO Inc.. The first subsystem, Macro, was created in 1977[1]. The MBTA has employed HASTUS since 1986. Throughout this evaluation, we will not only examine the potential advantages and deficiencies of computer-aided scheduling systems for transit authorities, but we will also explore the challenge of obtaining further savings from the computer-aided scheduling tool in the MBTA context. These empirical experiences should also give other schedulers, transit authorities, and researchers a better

[1] A detailed introduction to HASTUS will be presented in Chapter 3.

idea of possible impacts, benefits, challenges and further improvements needed for the application of computer-aided scheduling systems.

1.1. Motivation

Gavish, Schweitzer and Shlifer [30] and Stern and Ceder [37] define the bus planning process as consisting of several main phases: (1) Evaluating or forecasting the demand, (2) Establishing bus routes (vehicle routing), (3) Setting timetables, (4) Scheduling buses to trips to meet timetables (vehicle scheduling), (5) Assigning crews to meet a given schedule of bus trips (crew scheduling)[2].

Theoretically, the ideal solution of this transportation planning process is derived from a model in which all phases are formulated together. However, this is certainly too complex to be feasible because of the large number of variables and constraints. To solve this kind of problem, it is usual to break the planning process into several phases. Each phase is treated as an independent problem during the solution process with the output of each phase being used as the input to the next phase. This kind of planning process is referred to as sequential. Since it is obvious that there are many interactions between different phases, it becomes an important issue and a challenge how to break the complete process into tractable and feasible planning elements and how to achieve the proper combination of these elements.

There is no doubt that scheduling plays an important part in the operational planning process for any public transportation service. Poor scheduling in a public transportation system will not only affect the crews and the authority budget, but also the public because of its failure to provide the desired services effectively. Thus how to

[2] An introduction to the general scheduling process will be presented in chapter 2 of this thesis.

generate efficient and effective vehicle and crew schedules, which can satisfy the requirements and goals of crews, customers and the authority itself, becomes a critical challenge to the public transportation system manager and planner.

Researchers have been looking for applicable mathematical methods to solve complicated scheduling problems since the 1950's[3]. It has never been an easy task because of the large problem size, and a significant number of required constraints (the union contract, government rules, etc.), which present real barriers to success in these efforts. However, research has achieved a good degree of success and provides some useful models, algorithms, and methodologies for the scheduling problem. In the next two sections, we want to briefly review these approaches to scheduling problems.

Because of the large number of variables and constraints, useful and practical algorithms must be implemented in computer systems which support the scheduling process. The integration of algorithms into a computer system is thus a very important part of any application. Researchers have tried to use different methods and techniques to obtain better solutions with lower processing times. However, the tremendous size of the scheduling problem (especially the crew scheduling problem) is still one of the major difficulties in achieving a feasible and desired solution. Therefore, the ultimate test of solution approaches to scheduling problems is how effectively and efficiently the resulting models are being applied in the real world. Several computer-based scheduling systems have been developed and applied to many urban public transportation authorities. Some have claimed great successes in solving real scheduling problems. Not only can they produce feasible schedules for different authorities, but these schedules can also achieve savings in terms of the solution cost and time. As more this kind of application occurs, some important questions arise: How difficult is it to apply these computer systems

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[3] For example, Dantzig G. B., Fulkerson [65] used a linear programming model to solve a tanker scheduling problem in 1954.

effectively across different authorities. How easy is it to obtain feasible schedules with real savings? What kind of impacts other than the savings of cost and time can these computer-based systems have on the authorities?

We want to explore these questions in this thesis. We will focus on an evaluation of a scheduling system in a single context to gain some insights into the advantages and disadvantages of the current generation of computer-based scheduling systems. Hopefully, this research can give transit authorities a better idea about potential impacts, challenges, and benefits from applying computer-aided scheduling systems. It may also give researchers a clearer picture of the advantages, disadvantages, and possible improvements of current computer-aided scheduling systems. As a result, more effective computer-based scheduling systems for urban public transportation may be developed in the future.

1.2 The scheduling problem

Scheduling problems can be classified in several different ways based on the interests of the researcher: (1) Vehicle vs. crew scheduling problems, (2) Sequential vs. joint scheduling problems, (3) Scheduling problems in the urban public transportation systems and other modes, such as the airlines.

1. Vehicle vs. Crew Scheduling Problems:

Vehicle and crew scheduling problems are quite different from each other. Vehicle scheduling concerns the assignment of vehicles to the required services in an efficient and economical way, while crew scheduling considers the assignment of crews to cover all vehicle assignments. The objective of vehicle scheduling is to minimize the operating cost (the fuel, maintenance, etc.) while still covering all required trips. The capital cost (of the fleet) is sometimes also considered. Generally there are not too many constraints as the previously determined vehicle schedules makes vehicle timetable somewhat easier.

The objective of crew scheduling is to minimize the total crew cost. Aside from the wage cost, other costs, such as the health benefits, can also be important. Unlike vehicle scheduling, there are many constraints that have to be imposed on the crew scheduling problem. These constraints contain the work rules, unwritten rules, and government rules which govern the feasibility and cost of specific crew duties. They result in the complexity of crew scheduling problems. More discussions on these differences are presented in chapter 2 of this thesis.

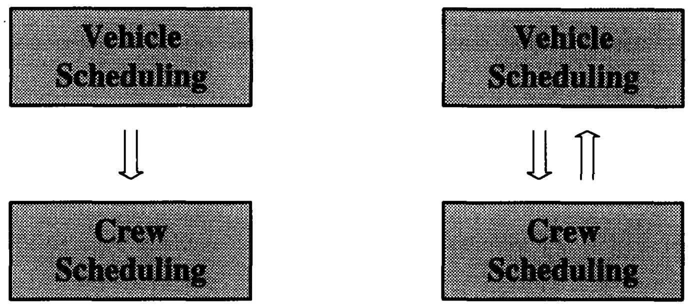
2. Sequential vs. Joint Vehicle and Crew Scheduling Problems:

There are many interactions that may occur between the vehicle and crew scheduling processes. The results and constraints on the vehicle scheduling process will affect the crew scheduling process and vice versa [7].

Thus trade-offs or adjustments between the vehicle and crew schedules through the scheduling processes have the potential to reduce the total cost. Some factors that dominate one scheduling level can also affect the other scheduling level. For example, union contract terms that have significant influence on the feasibility of solutions and costs of the crew scheduling problem could also affect the vehicle schedules, e.g., some adjustments to the vehicle blocks may be more efficient or economical under some union contracts. As Blais and Rousseau [19] showed in the case of Quebec City, the bus schedule can strongly affect the cost of the final crew schedule and some union contract constraints should be taken into account directly in the bus scheduling model.

Theoretically, if we want to get the true optimal solution to the overall scheduling problem, we have to combine these two processes together. Unfortunately, most of approaches to the vehicle/crew scheduling problem decompose the planning process in such a way that vehicle scheduling and crew scheduling are treated as separate problems.

Once the service frequency and the timetable have been established, the vehicle schedules are developed prior to the crew scheduling process as shown in *figure 1-1 (a)*.



(a) **The sequential scheduling process**

(b) **The joint scheduling process**

Figure 1-1: Two Views of the Scheduling Process

The reason for solving the problems separately in most practical approaches is that both types of scheduling problems tend to be NP-hard problems. It is very difficult to form a mathematical model and develop an algorithm taking into account all these elements at the same time, so it is much simpler to solve the problems individually than together. Given a set of vehicle schedules, the number of possible crew duties can be greatly reduced. The sequential process is very useful in keeping the crew scheduling problem size manageable. Therefore, it is still overwhelmingly the most popular approach to the scheduling problems.

However, some problems do arise from the sequential approach. First, the crew schedules are usually based on the vehicle schedules. Therefore, we can at best, obtain optimal or near-optimal crew schedules based on the given vehicle schedules. Certain solutions (even the optimal solution) may have been eliminated before crew scheduling begins. Second, it does not encompass re-evaluations of the vehicle schedules after crew schedules are developed. If the vehicle schedules are fixed, most of these interactions will be explicitly or implicitly ignored during the scheduling process, since it is difficult to incorporate feedback from the crew scheduling problems to help construct a better vehicle schedule.

As Bodin et al. indicated [1], with efficient and effective scheduling of vehicles or crews, we can not only save the operator cost by increasing productivity, but we may also obtain a tool for support in long-term planning or contract negotiations. Ideally and theoretically, if these two scheduling problems can be solved simultaneously, these problems could be addressed and solved within the scheduling process as shown in *figure 1-1 (b)*. Better results for both vehicle and crew scheduling, which can benefit crews, the authority, customers or even governments, may be found.

Some prior work has addressed this joint vehicle and crew scheduling problems and several papers addressing this topic [3][7][34][39] will be discussed in section 2.3.2.

3. Urban Public Transportation Systems vs. the Airlines:

Scheduling models, algorithms, and methodologies have been applied to different areas, such as urban public transportation systems, airlines, ships (tankers), etc. Research into computer-aided scheduling methodologies for urban public transportation systems and airlines are specially important and have been wildly reported. Many computer-aided scheduling tools for these two areas have been successfully developed and are being applied in the real world. Both similarities and differences can be found in this research and applications. By examining these similarities and differences, we can get a better idea about the state of development of scheduling methods in urban public transportation systems. Moreover, this comparison may stimulate improvements for current urban public transportation scheduling problems and computer tools.

The sequential nature of the scheduling process[4] and the core of the problem are similar in both application areas. However, these scheduling problems differ in several important respects. In the sequential scheduling process in urban public transportation systems, crew scheduling is usually more important than vehicle scheduling, because crew scheduling is more complex and has a higher share of total operating costs. However, aircraft scheduling sometimes will receive more attention than air crew scheduling because of the high capital cost associated with the aircraft fleet, as well as the competitive nature of the airline business.

Aircraft scheduling also usually has more constraints than other vehicle scheduling problems because of the safety issue which impose many operational constraints on aircraft schedules. The constraints of the crew scheduling problems between the two areas are also quite different. Apart from the union contract, safety concerns, the rules at other stations and in other government jurisdictions are also important for air crew scheduling problems. These differences are discussed in section 2.3.1.

1.3 Computer-based Scheduling Systems

Over the past twenty-five years, researchers have been trying to find ways to improve the efficiency and effectiveness of solutions to real world transit scheduling problems. Because of a large number of required trips, vehicles, crews, and required constraints, vehicle and crew scheduling have always been difficult tasks for schedulers and authorities. Therefore, the application of computer-based scheduling tools have

[4] In both applications of the sequential scheduling process, vehicle scheduling is performed first with crew scheduling based on the resulting vehicle schedule.

become very important. Many computer packages have been developed and implemented in transit authorities around the world in the past two decades.

In the early stage, computer-based scheduling tools focused on the development of "*one-pass*" procedures. After the input is available, the computer produced the schedule totally based on the designated mathematical algorithm. Because of the lack of powerful algorithms and the complexity of the scheduling problem (especially for crew scheduling), the schedules generated often were not produced acceptable, or failed to achieve significant improvement over the manual schedules. In addition, constraints and requirements vary significantly across authorities, making it very difficult to design a tool which is easily applicable in many different authorities. Therefore, most current computer-based scheduling systems tend to emphasize the active involvement of schedulers. These systems allow more interaction between the computer and schedulers. With help from the schedulers, the systems expect to produce more acceptable schedules across different authorities.

The general question to be addressed in this thesis is how effectively do these tools really work? What kind of benefits or impacts have they made on schedulers, crews, overall system performance and the public? Since the MBTA (Massachusetts Bay Transportation Authority, Boston) has employed a computer-based tool (HASTUS) since 1986, it serves as the key case study in this thesis. Thus we will present a detailed review and evaluation of this computer-based scheduling tool in the MBTA context.

1.4 Thesis Organization

The general vehicle and crew scheduling problems are discussed in Chapter 2 which also presents scheduling approaches applied in urban public transportation systems. In the section on urban transportation systems, some comparisons between the urban public transportation scheduling problem and the airline scheduling problem, and joint vehicle/crew scheduling problems is also discussed. In Chapter 3, we focus on the computerized scheduling programs developed for urban public transportation applications. The evolution of the computer-based scheduling tools and several important tools are described. An evaluation of the impacts of computer-based scheduling in the MBTA context is presented in Chapter 4. In Chapter 4, the impacts resulting from the installation of the computer-aided scheduling system (HASTUS) is first summarized. Several tests to estimate the possible benefits that this computer-based scheduling tool could achieve in the future are then performed. The first part of the evaluation is to assess the ability of HASTUS-Micro to find acceptable automated crew schedules for both a large (Cabot Garage) and a small bus garage (Albany Garage). Because there are many possible conditions and parameter settings in the crew scheduling process (and in HASTUS), the second part of the evaluation is to conduct sensitivity analyses based on the results derived in the first part of the evaluation. The impacts of different input files, and certain important parameters in the HASTUS-Macro file on Macro relaxed crew schedules and Micro automated optimized schedules for both bus garages are first assessed to examine if an acceptable optimized automated crew schedule can be found for either bus garage, and to examine if further improvements can be obtained. The impact of the relaxation of certain soft rules on the large bus garage (Cabot Garage) is then assessed. The final analysis evaluates the impact of different work rules in the Albany Garage case. The relationship between the Macro schedules and Micro schedules is especially emphasized. Chapter 5 presents our conclusions and suggestions.

Chapter 2: Review of Vehicle and Crew Scheduling Problems

This chapter gives a general introduction to transportation scheduling problems. The role of scheduling within the transportation planning process is first discussed. The general concepts of vehicle and crew scheduling problems are then presented. These introductions include the relevant components that directly or indirectly affect the scheduling problem. Their potential contributions to, and impacts on, the scheduling process and the final schedules are described along with the important elements that determine the final schedules and affect the efficiency and effectiveness of the scheduling process. The last section discusses urban public transportation scheduling problems. The general concepts, formulations as well as differences in the scheduling problems between urban public transportation and other modes (specifically airlines) are first presented. The joint vehicle/crew scheduling problem is then discussed.

2.1 Transportation System Planning

Transportation planning problems can be classified into three levels: strategic; tactical; and operational [2][3][27]. Scheduling is one crucial part of the operational planning level of the transportation system planning process as shown in *figure 2-1*. Scheduling is usually constrained not only by decisions at the operational planning level but also by those at the higher planning levels. Decisions at the strategic and/or tactical planning levels usually have fundamental and profound influence on the scheduling process. On the other hand, the nature of the scheduling process can also have some influence on the higher level planning decisions. Some examples are illustrated in the following section.

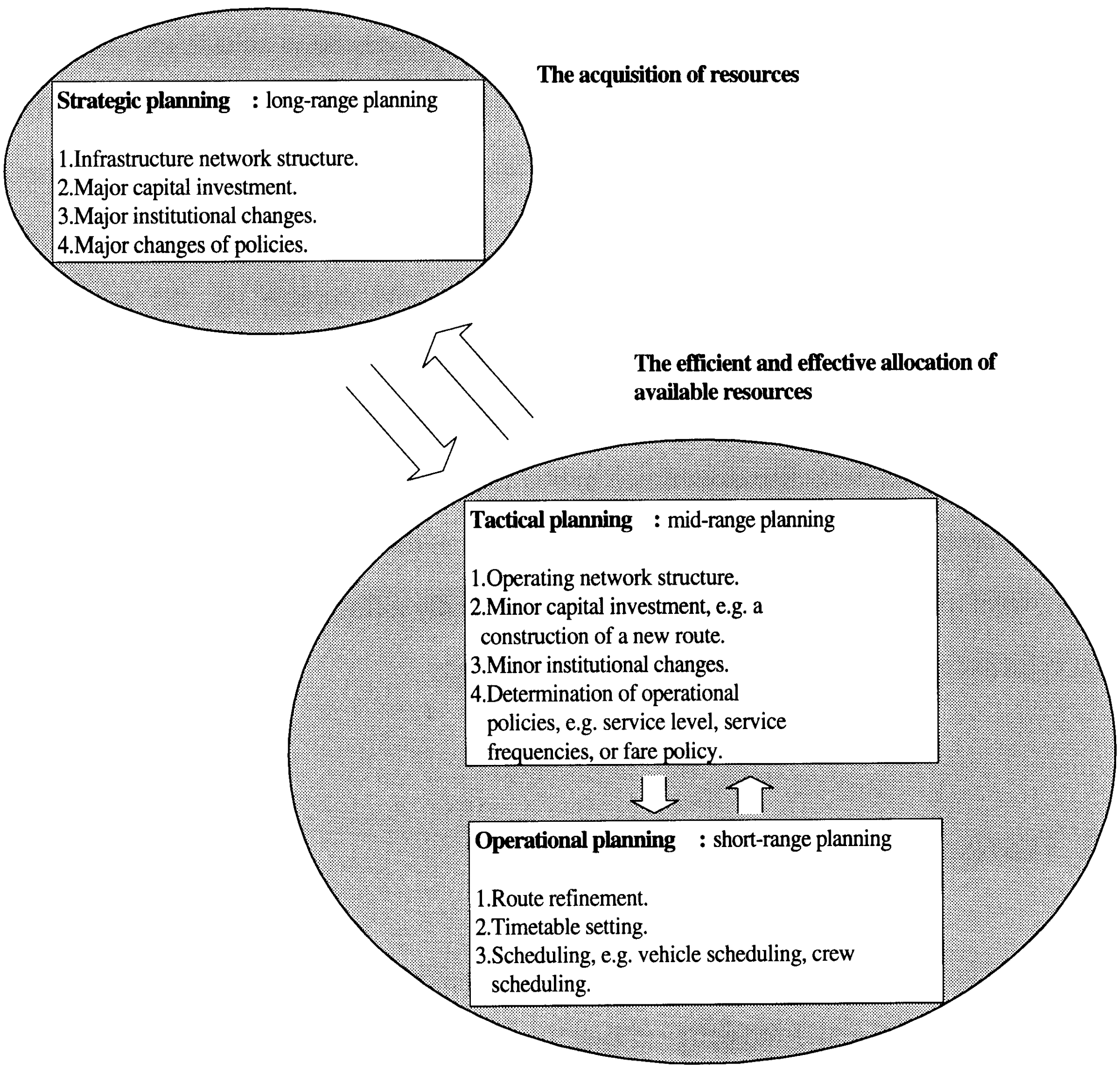


Figure 2-1 : Transportation Planning

Strategic planning:

Strategic planning concerns long-range development of the transportation system including major capital investments, major institutional changes and major changes of policies. The design and construction of the infrastructure network, the construction of a mass transit line or an airport, the acquisition of a new fleet, and deregulation (of the airline, trucking, rail or bus industry) can all be classified at this level of planning. Most of these decisions have major and long-standing effects on the transportation system as well as those served by it (the whole city, country or the public). Because of the large scale of investments and their significant effects, these decisions need to be supported by thorough and comprehensive studies. It will also frequently take a long time to implement these plans to achieve the planning goals.

The design of the infrastructure network will obviously affect the lower level design decisions including route studies, transportation demand, travel times, etc. The specification of the fleet will directly affect the available resources (types and/or quantities of vehicles) for the scheduling activities. Deregulation may result in revolutionary changes in the industry. For example, the introduction of hub-and-spoke networks after deregulation radically changed both vehicle and crew scheduling in the U. S airline industry.

Tactical planning:

Tactical planning consists of mid-range decisions such as route design, changes in fleet size, fare policies and the determination of service levels. These kinds of decisions have smaller impacts than those at the strategic planning level. Tactical planning (as well as operational planning) focuses more on the efficient and effective uses of the available resources while strategic planning emphasizes the acquisition and disposition of (principally) capital resources.

Tactical planning decisions have immediate effect on scheduling options since routes, fleet size, fare and service levels are all important inputs into the scheduling process. Route design determines travel times and (possibly) relief points. The service level such as frequency and the fleet size can influence the timetable (trips) and constrain the scheduling solutions. Another important factor is the transportation demand. The demand is determined by these tactical level decisions (as well as the strategic ones). However, the demand will be an input into the scheduling process.

Operational planning:

Operational planning governs short-term actions: the production of timetables; routing of specific vehicles; and the scheduling of vehicles and crews. These routing and scheduling problems are at the core of operational planning. Routing and scheduling activities are usually complex and time-consuming because of constraints on available resources including work force, vehicle fleet, information and budget[1]. Many concerns outside the agency itself also have to be taken into account, such as customers, union, government, the environment, etc. Although operational planning does not necessarily cost as much or have such a long-term impact as decisions at the two high planning levels, it is required for the implementation of any changes. Moreover, the public does not have to wait long to see the impacts from the changes at this level which thus may be more directly perceived.

Scheduling can provide important feedback to the higher planning level decisions. For example, while the determination of service frequency will affect the establishment of the timetable, then the schedules, after the implementation of the timetable, transportation demand may change and influence the services required for different periods and places. This should lead to reconsideration of the service frequency. Another obvious example

[1] The restrictions arise both within the operational level and from the two higher planning levels.

concerns the fleet size and the fleet type. If a good set of vehicle schedules can be achieved by a smaller fleet size, there is no reason for the authority to maintain a larger fleet at higher cost and lower utilization. In addition, if certain aircraft types, for example, can help produce more efficient and economical aircraft schedules, this information can certainly help the airline to define a more economical fleet.

2.2 Scheduling Problems

2.2.1 The Framework of Scheduling Problems

Figure 2-2 presents a general framework showing the factors which influence the scheduling process.

Transportation demand: Transportation demand is a key input to the establishment of timetables as well as to route and network design. It helps determine the sequence of stops and routes to be served, service frequencies and running times. It can be derived from historical data, such as passenger counts, running time checks, as well as demand models.

One characteristic of transportation systems that complicates both vehicle and crew scheduling is the difference between peak and off-peak demand levels. Although almost all industries have fluctuating demands for a variety of reasons, transportation systems (along with other service industries) can not store their outputs (the service provided) as an inventory to satisfy demand at other periods, nor can the peak hour demand be readily shifted to other periods. This inflexibility in both the demand and the service results in one of the main difficulties of scheduling problems in transportation systems.

The equipment (buses, aircraft, etc.) and crews should be able to meet the maximum requirement of the peak demand (or at least most of peak demand), and many of them may be idle or under utilized at other times (the off-peak demand). Therefore, a critical challenge in most vehicle scheduling and crew scheduling problems is how to minimize the effects of low off-peak utilization of equipment or crews and still keep satisfactory services at peak periods

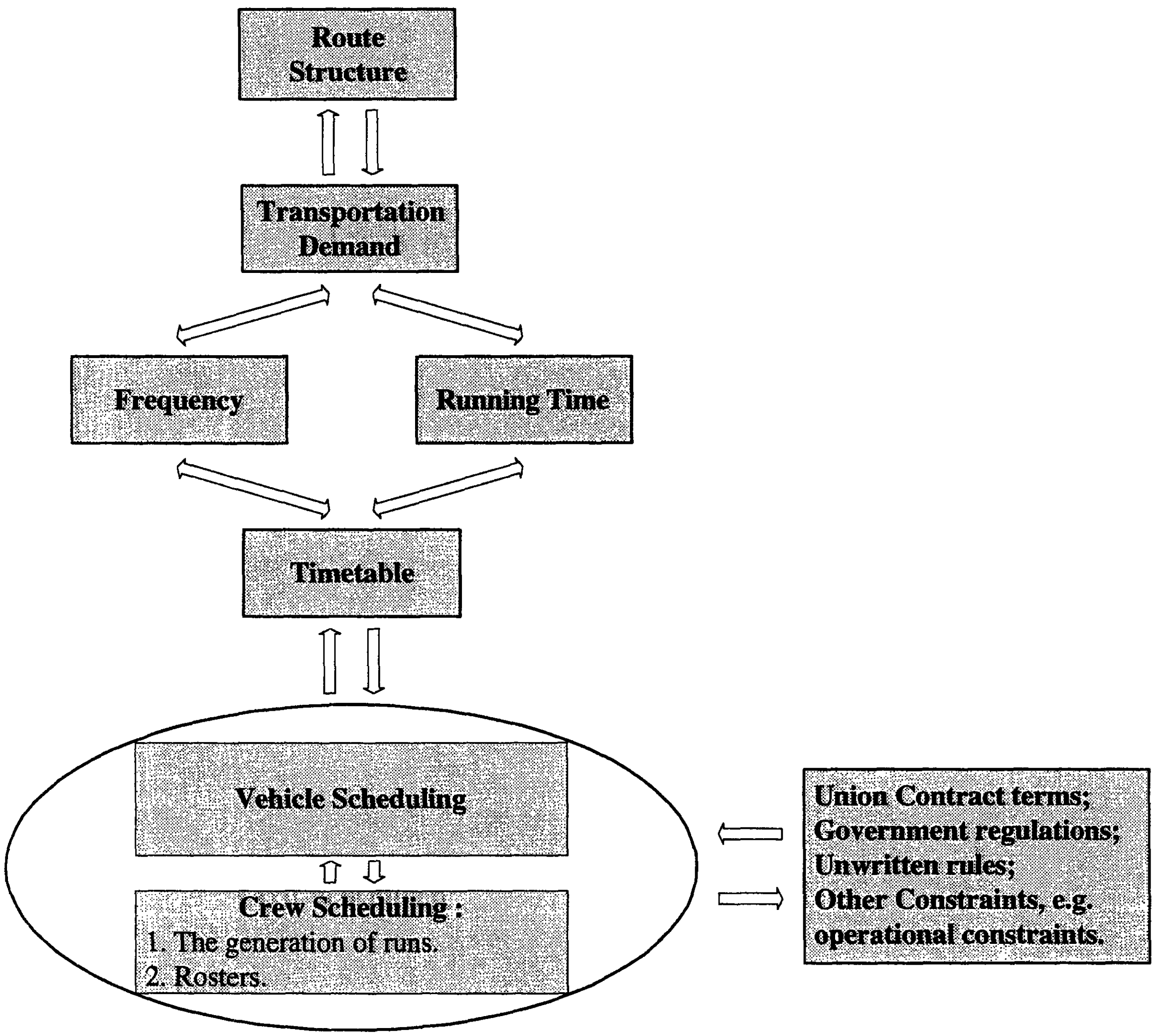


Figure 2-2 : The Scheduling Problem

Running time & Service frequency: As mentioned above, routes to be served and the sequence of stops are designed based on the transportation demand. Consequently, the expected running times on these routes or between stops (including garages) for different periods (morning peak, evening peak, off-peak), different day types (weekday, Saturdays, Sundays, holidays), different seasons, and different duty types (regular trips or school trips) can also be determined (or predicted).

These running times are not only important to help determine the service frequency as well as construct the timetable, but they are also necessary for the construction of the vehicle and crew schedule. For one thing, it is impossible to build the vehicle schedule without knowing the pull-out, pull-in and deadheading times. This is also true for the crew schedule. As we will discuss later, swing and crew deadheading can help produce efficient and cost-effective crew schedules. Without this information as well as the travel times between stops, even if it is still possible to build a set of crew schedules, it could be costly.

As mentioned by Odoni et al. [2], most transit authorities set frequencies of service to satisfy transportation demands at a specified service level, such as the number of passengers per vehicle at peak load points, while minimizing the number of vehicles required. Since the timetable is primarily based on service frequencies, in a sequential scheduling process, this also implies that the frequency of service not only determines the basics of timetabling but also vehicle and crew scheduling, because vehicle scheduling is based on the timetable and crew scheduling follows from the vehicle schedule.

Timetable: With the major inputs of the service frequency and the running times, the planned services that contain information on specified departure and arrival times, and specific departure locations and destinations are determined. In this thesis, it will be called the timetable (it is also called the flight schedule in the airline industry). The timetable is usually assumed to be a fixed input for most scheduling problems in both the airlines and urban public transportation systems. The resulting schedules (either vehicle or crew schedule or both) are sometimes used in a feedback loop to adjust timetables (retiming)[2].

Vehicle scheduling: Vehicle scheduling determines the assignment of each vehicle in the fleet according to a given timetable with a desired objective such as minimum cost or maximum profit. The fleet size and vehicle types are the major concerns in vehicle scheduling. In the airline industry, both the fleet size and aircraft types are equally important, whereas fleet size is more important in urban public transportation systems since there is generally less variability in vehicle type.

The vehicle schedule is very important not only for the assignment of vehicles but also for the crew schedule. In the sequential scheduling process, the crew schedule will be heavily influenced by the vehicle schedule. A good set of vehicle schedules can facilitate the creation of a more efficient crew schedule.

Crew scheduling: Crew scheduling can be divided into two parts in terms of the time horizon: (1) the generation of the short-period (e.g. daily) schedule[3]; (2) the roster for a longer period (a week, a month, etc.). A daily crew schedule is called *a run* or duty in urban public transportation systems. The definitions of these and other terms are given in *Appendix A*.

The crew scheduling problem is to assign operators (or crews) to cover the vehicle schedule, i.e. all trips, efficiently and effectively under given constraints. For the traditional planning process referred to in Chapter 1, crew scheduling is based on given vehicle schedules. Along with given vehicle schedules, the information on possible relief points is

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[2] One computerized system with this kind of function is discussed in *chapter 3:* the VAMPIRE system.

[3] In most papers, the term *vehicle (or crew) schedule* indicates one daily assignment for a single vehicle (or crew) while the term *the vehicle (or crew) schedules* indicates daily assignments for the whole fleet (or for all crews).

very important in crew scheduling problems. The crew scheduling process needs this information to decide how to cut and combine the vehicle schedules into crew duties. A roster is a set of runs representing a schedule for a longer period, e.g. one week or one month. Rosters are traditionally selected by crews based on seniority, but there is a trend to assign rosters with balanced work loads or pay hours between crews. The rostering problem is not dealt with in this thesis (for discussion of this issue, the reader is referred to Bodin et al. [3]).

Union contract terms, government regulations, company policies and unwritten rules usually dominate the crew scheduling problem. They are also becoming more and more important to vehicle (aircraft) scheduling problems. Not only can they have significant impacts on scheduling problems, but some scheduling approaches could also be useful in evaluating possible changes to union contract terms, regulations or policies for the union, government or the agency. Even in a sequential process, crew scheduling can still influence the vehicle schedule. For example, we can reduce meal breaks, deadheading cost or make-up[4] times by adjusting the vehicle schedule.

2.2.2 The Relationship between Routing and Scheduling Problems

While this thesis focuses on scheduling problems, it is also important to recognize the relationship between routing and scheduling problems, for there are some similarities between the two kinds of problems. Routing problems determine the sequence of locations to be visited by one, (or more) vehicle for pick-up or delivery services at the minimum cost[5]. Scheduling problems can be seen as basically the same as routing problems except that the service times (the starting, delivery and ending time) at every

[4] The make-up time is the difference between the guaranteed daily pay hours and the (smaller) platform time. It is the time a driver is paid without working. A good set of crew schedules should keep this kind of extra pay as low as possible.

[5] The minimum cost is generally the primary objective, but not the only one.

location are clearly specified (the timetable in mass transit operations)[6]. As Bodin et al. [3] indicate, routing problems are primarily spatial problems, but scheduling problems have to be concerned with both time and spatial relationships, e.g. a single vehicle (crew) can not serve two locations simultaneously [1][3].

Scharge [12] classified routing and scheduling problems into three types : (1) Arc-based problems -- specific arcs (routes) should be covered; (2) Node-based problems -- specific nodes (locations) should be served; (3) The combined problem -- specific arcs and nodes should be served. In general, most scheduling problems specify certain routes (or paths) and locations based on advance information on demand or service frequencies. These data are assumed fixed in scheduling problems. For example, bus routes and timetables are fixed as the input to scheduling problems in public transportation systems as mentioned in Chapter 1 (also see Gavish et al. [30] or Stern and Ceder [37]).

The scheduling problem itself can also be formulated and solved as a network problem [3][9] as illustrated in *figure 2-3* in which each pair of nodes represents a task[7], and each path stands for a single vehicle (or crew) schedule. The solution is to cover all tasks through the feasible paths with minimum cost[8]. In *figure 2-3 (a)*, a vehicle schedule starts from the top start node, pulls out of the garage, goes through the first revenue-trip arc, the second revenue-trip arc, and eventually pulls back in to the same garage. Thus a vehicle schedule is represented by a path. The long arc between two revenue-trips could represent a pull-in and a pull-out, or imply that the vehicle is idle at the station (without returning to the garage or performing any duty). Another possible network representation is shown in *figure 2-3 (b)*. The cyclic path, which represents a vehicle schedule, starts from the bottom garage node, follows the capital-cost arc to the top, goes through a pull-

[6] Magnanti [9] presents a detailed discussion of vehicle fleet planning (routing and scheduling) problems, focusing on heuristic and exact solution methods for routing problems.

[7] In this thesis, the meanings of *task*, *trip* and *a piece of work* are identical.

[8] The *cost* could be the capital cost, the operating cost or any other cost function. For example, some formulations directly set up the objective function to minimize the number of paths which also means to minimize the vehicles required, i.e. the capital cost.

out arc, revenue-trip arcs (or even a deadheading arc), and pull in to the garage. More discussion about this kind of network formulations is presented in section 2.2.4.

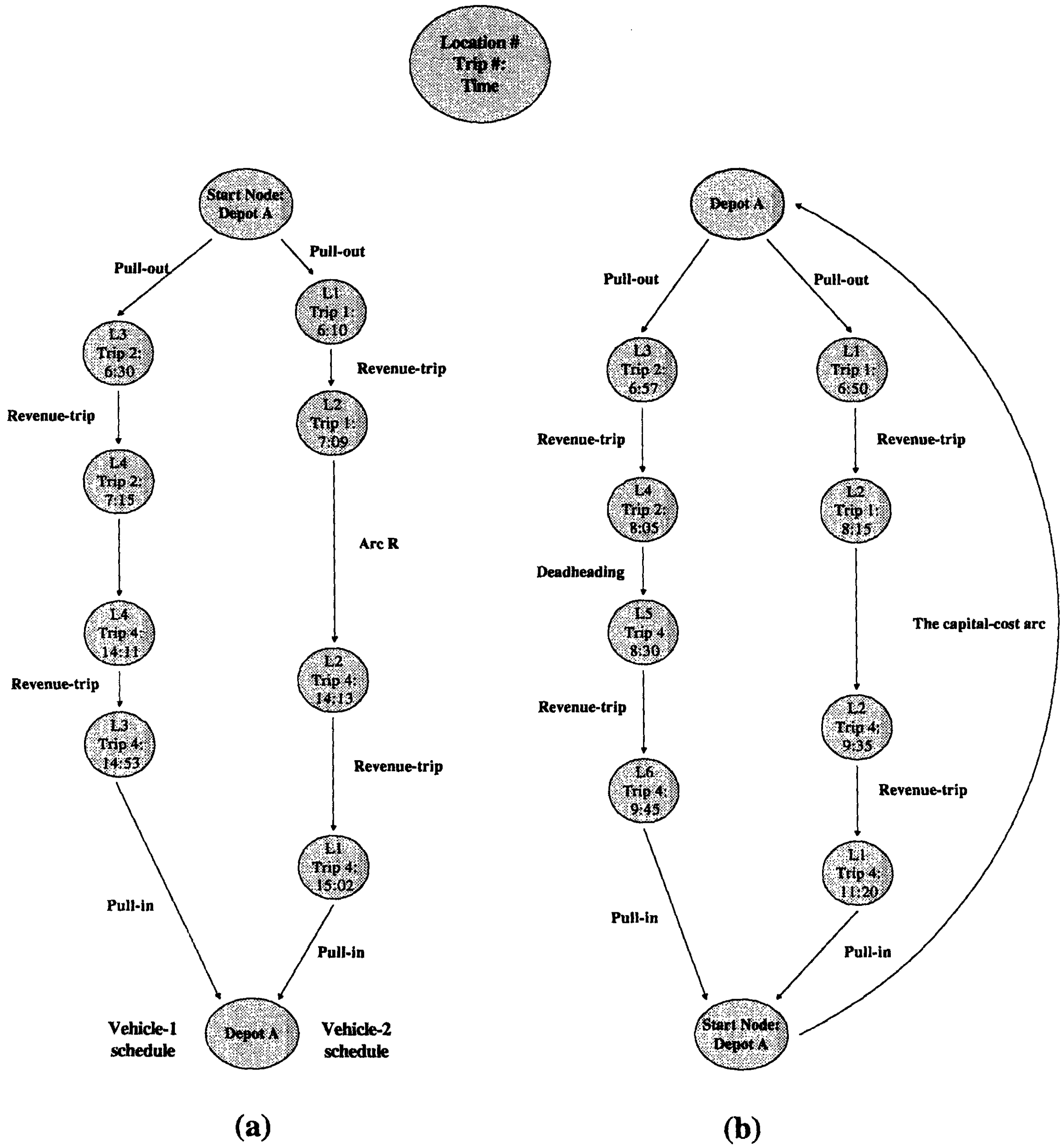

Figure 2-3: Network Formulations

2.2.3 The Application of Computers in Scheduling Problems

The formulations of scheduling problems are complex because they include many variables and constraints. Except for the basic vehicle scheduling problem, most vehicle scheduling problems and crew scheduling problems are classified as NP-hard problems. The complexity of scheduling problems mostly results from union contract terms, particularly for crew scheduling problems. It is also increasingly important for the vehicle scheduling problem to take into account some of these union contract terms.

Union contract terms are tending to become more and more complex adding to the difficulty of producing schedules both rapidly and effectively. As Smith and Wren [28] indicate, it is a very difficult task for manual schedulers to form valid crew duties efficiently while accommodating the many constraints. They have to check repeatedly the feasibility of alternative duties and the cost effects of the schedule during the process. According to Mitchell [22], a systemwide crew schedule could take at least one person-year of effort in the Southern California Rapid Transit District (now the Los Angeles Metropolitan Transportation Authority). Such time-consuming work makes frequent changes in the existing schedule impossible. It also makes forecasting the impact of changes in operating conditions or union contract terms efficiently and effectively extremely difficult. As Ball et al. stated [47], *lack of computerization makes it impossible to determine vehicle and crew costs as a function of changes in work rules, to determine the sensitivity of crew and vehicle costs to changes in routes and to determine the effects of system growth on operating costs.* Thus to simplify the scheduling process and allow planners to pay more attention to the evaluation and improvement of services, the application of computers is essential.

The development of HASTUS-Macro was one effort to respond to these expectations since it can be used as an independent tool for cost estimation and to assist in union contract negotiations. Blais and Rousseau describe this application in detail in [19]. Because of the available quantified estimate of the impacts of a proposed change, the company may be better able to resist infeasible and/or costly proposals from the union or governments and save money and time.

Cost saving is also a very important factor for authorities in applying computers to the scheduling process. Savings resulting from these applications of computers have been shown in several cases. Gavish et al. [30] implemented their model and algorithm at a public transportation company and argued that a 5-10% saving of the fleet size required in the peak hours and 10-25% saving in deadheading and idle times could be expected compared with the originally manual scheduling system. According to Koffman and Rousseau [81], the introduction of computer scheduling at the Ottawa-Carleton Regional Transit Commission (OC Transpo) has also achieved significant savings. For example, the use of computerized vehicle scheduling (interlining) in 1975 resulted in bus savings of about 7%, and an annual cost saving of $3 million. Another vehicle scheduling function (trip shifting) also resulted in bus savings of about 3% in 1990 for OC Transpo.

Aside from the dollar-cost saving, the saving of schedule preparation time is also quite important, and can be significant. Computers can help schedulers save tremendous amount of paper work required for manual scheduling and reduce the production cycle of a set of schedules. It can also reduce the number of schedulers required.

In the urban public transportation field, because of the importance of the applications of computers, there have been six workshops[9] about computer-based scheduling held around the world in the last two decades[10].

[9] The six workshops were held in Chicago (1975), Leeds (1980), Montreal (1983), Hamburg (1987), Montreal (1990), and Lisbon (1993).

[10] An operational research workshop: AGIFORS (Airline Group of the International Federation of Operational Research Societies) also provides a similar forum for both operational research models and applications of computer systems in airlines.

2.2.4 Vehicle Scheduling Problems

In the vehicle scheduling process, vehicles are assigned to serve the demand economically and effectively. Each trip in the timetable will be covered by a single vehicle, so as achieve, specified objectives, such as minimum cost or maximum profit, while satisfying various constraints. The determination of a suitable formulation (or model) and the relevant cost function as well as the constraints will significantly affect the final schedule to be generated, and also affect the following crew schedule which is heavily dependent on the vehicle schedule in the sequential process.

Objective function:

Scheduling problems usually set cost minimization as the main objective[11]. This objective can be formulated in terms of the minimization of the number of required vehicles (capital cost)[12], operating cost or a combination for different concerns. Some models use a composite objective instead of a single one. Gavish et al. [30] designed such a composite objective for their bus scheduling problem. They use two important objectives: a primary objective (for both the peak and off-peak hours) and a secondary objective. The primary objective is to minimize the number of buses during peak hours and to minimize deadheading costs during off-peak hours[13]. The secondary objective is to minimize changes in the existing schedule. The latter objective is not a common concern in most vehicle scheduling problems. As Gavish et al. [30] mention, the minimization of fleet size may also increase deadheading and thus increase operating costs and operations and management difficulties. To deal with these conflicts, we can try to find a suitable objective function that can minimize the total cost (combined operating and capital cost).

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[11] Profit maximization is also a popular objective, especially in the airline industry.

[12] To minimize the fleet size is a very popular objective, but sometimes restrictions will not allow the system to have the minimum fleet size. For example, if interlining in a bus system is not allowed, then the total fleet size for the system may not be minimized [7].

[13] To simplify the process, only one objective is generally taken for both peak and off-peak hours for most scheduling problems.

Gavish and Schweitzer [30] defined a cost function whose cost coefficients reflect either the capital cost, or the combination of the cost of deadheading, the cost of driver's travel time, the cost of changing the existing duty and the interlining cost for different conditions.

For the aircraft scheduling problem, minimizing the fleet size is usually not a primary concern. The airlines' first focus is to assign suitable types of aircraft to perform the flight schedule with a minimum total cost (or maximum profit). The minimization of the fleet size for each fleet type can be achieved later if needed.

How to define a proper cost function is always a critical issue in scheduling problems, for it will substantially affect final results of the schedule, such as vehicle block patterns. The determination of a cost function is not just an independent algebra or accounting problem; it has much to do with the characteristics and the formulation of the problem. For example, if we want to use the network formulation (shown in *figure 2-3*) to find the ideal schedule, the way we assign the appropriate operating cost, including deadheading, pull-in, pull-out, and revenue-trip costs or the capital cost for each arc should be consistent.

If we are just concerned with the minimization of the operating cost regardless of the capital cost, the problem is much easier. We can directly assign all operating costs to different types[14] of arcs in formulations similar to those in *figure 2-3*. However, if we want to reflect the total cost, i.e. operating cost and capital cost, the problem is somewhat different. It is not simply a matter of allocating the capital cost of a certain type of vehicle to trips and expecting the formulation to work well. There are some basic vehicle scheduling models, such as *figure 2-3 (a)* discussed in Ball et al. (the VSP model) [3] and Scott (the VSP1 model) [7] and *figure 2-3 (b)* which illustrate the possible problem in the allocation of the capital cost. As they indicated, if the capital cost is imposed on the pull-

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[14] These types consist of deadheads, pull-ins, pull-outs, and revenue trips.

ins or the pull-outs in *figure 2-3 (a)*, or the capital arc always connects with the pull-in and pull-out arcs as in *figure 2-3 (b)*, these models (or formulations) will make the final schedules favor longer layovers and deadheads. The models will prevent additional pull-ins or pull-outs for any scheduled vehicle during the day due to the heavy cost penalty, even though there should be no real additional capital cost associated with them.

Some research, therefore, has sought other cost definitions, or adjustments to the network model to solve this kind of problem. Ball et al. [3] suggest that the capital cost be imposed on a pull-in or pull-out arc only in the morning peak period[15]. Thus if we can carefully assign costs to certain types of arcs and set up some constraints for the network model, the intermediate pull-ins (or pull-outs) can be employed in the solution while maintaining the concern for total capital costs. For example, with the network model in *figure 2-3 (a)*, we can build a constraint in which pull-in and pull-out trips will replace a long arc such as Arc R in the vehicle-2 schedule if this arc is not an operating arc and has a duration longer than a certain time.

Scott [7] suggests an improved model based on the formulation of *figure 2-3 (b)*. The model adds one artificial depot for each node except for two real depot nodes. A pull-out arc from a corresponding artificial depot node will be added to the node that represents the start time of each trip, and a pull-in arc to a corresponding artificial depot will be added to the node that represents the end time of each trip. In this way, pull-out arcs or pull-in arcs do not have to connect the capital arc all the time and can still have pull-outs and pull-ins in the middle of a vehicle schedule. Therefore, more accurate, economic, and reasonable schedules can be obtained with the employment of intermediate pull-ins and pull-outs.

Bennington and Rebibo [69] introduce the network structure used in RUCUS-BLOCKS (vehicle scheduling) as shown in *figure 2-3 (b)*. BLOCKS employs the network

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[15] The vehicle demand in a peak period is typically the total vehicles required. Under this assumption, we can choose the maximum demand for vehicles in peak periods.

in a somewhat different way. As mentioned before, a path in other network models represents a vehicle schedule. However, a path in BLOCKS represents a block. Thus, if a vehicle schedule contains at least two blocks, intermediate pull-ins and pull-outs are always possible. Of course, the cost of the capital-cost arc is defined as the cost to bring in a vehicle to serve a block, not a complete schedule[16], and extra work is needed later to match these blocks to form the vehicle schedule.

Constraints:

Recognizing the limited resources (vehicles, capital), operational restrictions, the feasibility of schedules, and regulations, certain constraints will be imposed in the scheduling process. These constraints could be the limits on available fleet type or fleet size, maintenance requirements, the constraints that make the scheduling model complete and feasible, etc. In general, aircraft scheduling have more constraints than transit scheduling as shown in *Table 2-1*[17]. Fortunately, vehicle scheduling (or aircraft scheduling) has fewer constraints than crew scheduling making formulation of the vehicle scheduling problem somewhat easier.

Table 2-1: Typical Operational Constraints for Aircraft Scheduling

1. Limits on arrivals or departures at a station during the day.
2. Limits on the number of overnight stays of aircraft at a station.
3. Limits on the number of stations served.
4. Limits on slots and daily service.

[16] Sometimes, it will be difficult to decide the additional cost. For a set of vehicle schedules, we can allocate the capital cost according to the existing fleet size. However, we usually do not know about how many blocks will be generated before the generation of the final schedule.

[17] Also in Abara's [53].

Formulation:

Many scheduling problems (both vehicle and crew) are formulated as either set partitioning problems or set covering problems. These formulations will generally lead to huge problem sizes and result in great computational requirements, thus some methods (or constraints, rules) are usually imposed to restrict problem size or to decompose the problem into more manageable subproblems. In general, the approach to deal with set partitioning or set covering problems (in both vehicle and crew scheduling) is first to relax the integer constraint and solve the resulting linear problems, then to try to move to an integer solution.

Vehicle scheduling problems can generally be classified into five different types[18]: VSP: the single depot vehicle scheduling problem; VSPLPR: the vehicle scheduling problem with length of path restrictions; VSPMVT: the vehicle scheduling problem with multiple vehicle types, VSPMD: the vehicle scheduling problem with multiple depots; VSPTW: the vehicle scheduling problem with time windows. Most urban public transportation scheduling problems are of the VSP and the VSPMD type, while most aircraft fleet assignment problems are of the VSPMVT type. We will present more detailed on the fleet assignment problem in a later section of this chapter.

The models used in all vehicle scheduling problems generally can be derived (or extended) from the VSP model shown below. RUCUS employs a model that is almost identical to this model for vehicle scheduling. This model is based on the network formulation illustrated in *figure 2-3 (a)*.

Constraint (2.2) is a flow balance constraint[19] with $b(i) = 0$ for all nodes except for the source and sink node (depot). This is also like the transshipment problem. Constraint (2.3) guarantees that a vehicle (path) is assigned to serve each task (node) exactly once.

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[18] Many different constraints or different conditions can also be used to classify vehicle scheduling problems as shown in [1]. For example, scheduling problems with random instead of deterministic demands.

[19] It is also called flow conservation, nodal balance or Kirchhoff equation: It indicates that the flow

$$Min \quad \sum_{(i,j)\in A} c_{ij}\, x_{ij} \tag{2.1}$$

St.

$$\sum_{j:(i,j)\in A} x_{ij} \; - \sum_{j:(j,i)\in A} x_{ji} = b(i) \qquad i \in N - \{s, t\} \tag{2.2}$$

$$\sum_{j:(i,j)\in A} x_{ij} = 1 \qquad i \in N - \{s, t\} \tag{2.3}$$

$$0 \le x_{ij} \le 1 \qquad (i,j)\in A \tag{2.4}$$

x_{ij} : *integer, number of vehicles that traverse arc(i,j)*

$G = (N,A)$; G : *a network*
N : *a set of nodes*, A : *a set of arcs*

C_{ij} : *Arc* (i,j) *cost*

s : *Sink node*, t : *Source node*

The capacity constraint (2.4) along with the integer constraint indicates that:

$$x_{ij} = \begin{cases} 1 & \text{if arc}(i,j) \text{ is served by a vehicle} \\ 0 & \text{otherwise} \end{cases}$$

Some models use set covering models which allow vehicles to deadhead. In this case, Constraint (2.4) become:

$$\sum_{j:(i,j)\in A} x_{ij} \ge 1 \qquad i \in N - \{s, t\} \tag{2.4'}$$

---

may be neither created nor destroyed in the network, see Bazaraa et al. [6].

We assume that these vehicles carry out closed trips (or round trips or pairings for airlines) rather than open trips, meaning that each vehicle has to pull out and pull in at the same depot. The assumption is to simplify the minimum cost flow formulation as shown in *fig 2-3*.

2.2.5 Crew Scheduling Problems

Crew scheduling is also called crew pairing in the airline industry, and the manual crew scheduling process is sometimes referred as run-cutting. In urban public transportation systems, the crew scheduling process cuts the vehicle blocks into pieces and forms these pieces into a set of crew runs (also called duties). There are three basic types of crew runs (or duties): straight, split, and tripper. For example, a spreadover duty, as mentioned in Parker and Smith [41], which covers both peaks and has a long break (usually unpaid) in the middle, is one common form of split shift. A detailed introduction to scheduling terminology is shown in *Appendix A*.

In the airline industry, each crew is assumed to be assigned to only one aircraft type [40], thus crew scheduling is considered separately for each aircraft fleet type. After the aircraft schedule is completed, the crew scheduling process groups flight legs from the aircraft schedule into pairings.

Objective:

The general objective is to minimize the total cost under certain constraints. In crew scheduling for urban public transportation systems, the vehicle schedule can be cut into pieces of work only at designated relief points at which crews can be relieved. A relief point can be a garage, depot or simply a stop along a transit line or bus route.

The determination of a crew cost function is based on the pay rate and work hours. It is much easier than in vehicle scheduling, for there is no "capital cost" associated with the crews. The potential problems discussed in vehicle scheduling that can give rise to many complications in the formulation do not arise here.

Constraints:

The constraints consisting of union contract terms, government regulations, authority policies and unwritten rules play an important role in crew scheduling problems. Detailed discussions of these work agreements[20] in urban public transportation are given in Sharp [20], Blais and Rousseau [19], Smith and Wren [28], Manington and Wren [64], and similar discussions for the airline industry are given in Abara [53], Arabeyre et al. [55] and Barnhart et al. [63]. These work rules include guaranteed pay or compensation for overtime in the urban public transportation system, or minimum rest time for certain spread time, and maximum flying time for a duty period for an air crew schedule.

Tables 2-2 and *2-3* show some general work rules in urban public transportation systems[21] and in the airlines respectively. Not only do these agreements increase the operating cost, but they also complicate the scheduling process. For example, an agency with 2000 peak vehicles and 4665 full-time drivers as SCRTD (Southern California Rapid Transit District) will have significantly more operator pay hours than vehicle hours, e.g. 8.6 million pay hours and 7.1 million vehicle hours [22].

Since the key terms of the agreement must be incorporated as constraints into crew scheduling models, it greatly complicates the problem. The number of constraints and variables in the formulation of a crew scheduling problem can make it unmanageable. In general, these also make the crew scheduling problem much more complicated than the vehicle scheduling problem.

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[20] A discussion about a related topic: *working conditions* is given in [23].
[21] The work rules used in the MBTA are also shown in *Appendix B*.

Table 2-2: Example of Urban Public Transportation System Work Rules

1. Minimum guaranteed 8-hour pay per day for a full-time operator.
2. Maximum 13-hour spread per run.
3. A paid allowance for sign-on and sign-off per day is 20 minutes.
4. No more than 3 pieces for a full-time run.
5. Minimum 2 hours for a piece of work.
6. Maximum 5 hour's work without a meal break is permitted. A meal break is at least 30 minutes.
7. At least 50% of total runs should be straight runs. Sunday runs should be 100% straight runs.
8. Minimum time of an unpaid break is 40 minutes.
9. Maximum number of unpaid breaks is 1, i.e. if the number of breaks exceeds this number, extra breaks should be paid.
10. Overtime rate: 1.5 times regular pay rate
11. Spread premium: 1.5 times regular pay rate after 10 hours for a duty; 2.0 times regular pay rate after 11 hours.

Table 2-3: Example of Airline Work Rules

1. Maximum number of flight legs in a duty period.
2. Maximum flying time and the maximum spread per duty period.
3. Maximum number of times that a pilot can change planes per duty period.
4. Minimum and maximum connect time between consecutive flights in a duty period.
5. Minimum rest time for a pilot after a duty period.

Union contract terms also increase the difficulties in developing a generally applicable computer program, since particularly in public transit systems, union contract terms vary considerably from one company to another. As Parker and Smith state [41], at least one totally different constraint would be found in every new case, and some new feature has to be introduced into the program to deal with these special problems. This problem is not as severe in the airline industry, because union contract terms in the airline industry tend to be much more similar across airlines [32].

Union rules result from the special characteristic[22] of transportation systems: the difference between peak and off-peak service demands as introduced in section 2.2.1 [18][20][21][24]. Because of this difference, more split shifts or trippers will arise and more part-time operators may be desirable. Part-time duties are very important for the urban public transportation scheduling task and for authorities. For schedulers, part-time duties can be used to cover one or two peak periods which usually cannot be assigned into full-time duties (i.e. leftover small pieces of work) because of work rule restrictions (e.g. the duty-length constraint, the overtime constraint, and the spread-length constraint, etc.) as well as insufficient available full-time operators. In transit authorities, unlike full-time operators, part-time operators usually are not paid spread premiums. Thus the employment of part-time operators may be more economical than full-time operators. To reflect the need to protect operators' welfare, most union contract terms have a large number of restrictions and compensation terms for crew duties [19][21][24].

Formulation:

Following the general assumption that the vehicle schedule is given, the crew scheduling problem can generally be formulated as a set covering (or set partitioning) problem[23]. The introduction to a related type of crew scheduling problems (counter staff,

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[22] This characteristic also affects the vehicle scheduling mentioned in *section 2.2.1*.

[23] Similar set covering formulations as shown below are also presented in [2][3][28][42].

maintenance staff) is shown in Rousseau [32]. Basically, they have the similar formulations and algorithms as those presented in this paper.

$$Min \quad \sum_{j=1}^{n} c_j x_j \tag{2.5}$$

St.

$$\sum_{j=1}^{n} a_{ij} x_j \geq 1 \qquad i = 1, 2, \ldots, m \tag{2.6}$$

$$\sum_{i=1}^{n} b_{ij} x_j \geq d \qquad j = 1, 2, \ldots, n \tag{2.7}$$

$$x_j = \begin{cases} 1 & \text{if crew duty } j \text{ is in the schedule} \\ 0 & \text{otherwise} \end{cases}$$

$$a_{ij} = \begin{cases} 1 & \text{if trip } i \text{ is served by the crew duty } j \\ 0 & \text{otherwise} \end{cases} \qquad ; j = 1, 2, \ldots, n$$

C_j is the cost of crew duty j based on the work performed by duty j and the pay rate. Constraint (2.6) means that each piece of work (or trip, task or flight leg) must be covered by at least one crew schedule(a crew run or a crew pairing). Constraint (2.7) could be any union contract or company constraint shown in Mitra and Welsh [42]. For example, we can set a manpower constraint for total operators as:

$$\sum_{j=1}^{n} x_j \leq N \qquad N\text{: total number of crew} \tag{2.8}$$

We can also set a time constraint for guarantee pay hour, minimum platform time, or minimum (or maximum) spread as in Constraint (2.9). For example, $x^{c}{}_{j}$ is a binary variable and equals 1 only when the spread length of the feasible duty (X_j) is greater than or equal to the minimum spread-length constraint (T_K). Thus Constraint (2.9) implies that, among all K feasible duties, at least M duties must have spread-lengths greater than or equal to T_K.

$$
\begin{aligned}
&\sum_{j \in K} (t_j - T_K)\, x^{c}{}_{j} \geq 0 \quad K(\textit{feasible duties})\text{: } 1,2,\ldots,k \\
&\sum_{j \in K} x^{c}{}_{j} \geq M
\end{aligned}
\qquad (2.9)
$$

If the inequality in (2.6) is replaced by the equality, it becomes a set partitioning problem. A set partitioning formulation is used when crew deadheading (or the overlap of two duties) is not permitted[24] [32][41]. It insures that each piece of work is carried out by exactly one crew schedule [28][31].

These basic set covering and set partitioning approaches have been used both in urban transportation systems and in the airlines [33][40].

[24] When deadheading is permitted, it implies that trip i could be served by more than one crew duty.

2.3 Urban Public Transportation Vehicle/Crew Scheduling Problems

2.3.1 Urban Public Transportation Systems vs. the Airlines

It is interesting to compare and contrast the scheduling problem in the airlines and urban public transport areas. The basic concepts of the scheduling problems are very similar, and the framework presented for the urban public transportation system (section 2.2.1) is compatible with the airline scheduling problem. Transportation demand is assumed fixed for both the aircraft and air crew scheduling problems. Air crew scheduling (crew pairing) is still based on flight schedules and aircraft scheduling. In addition, we find a strong resemblance in the meanings of terms used in the two fields (See *Appendix A*). However, the differences also are significant in terms of time horizon, service frequency, timetable construction, competition, cost function (objective) and constraints, etc. Through the comparison between these two areas, we can have a better idea about the key attributes of the urban public transportation scheduling problem.

1. Time horizon: The time horizons of scheduling problems between the two systems are quite different. Aircraft and air crew scheduling usually must deal with a longer period because of the operational characteristics, especially for international airlines. The difference is quite obvious when we look at the components of a schedule: one crew run is a daily assignment of the bus crew while a pair for an air crew schedule could cover one week.

The difference between the time horizon will lead to different concerns. For example, bus scheduling in the MBTA does not have to be particularly concerned with maintenance requirements. Since it is a daily schedule and the schedule is performed within the Metropolitan Boston area, it is easy to find enough time for any bus to undergo routine maintenance[25]. Besides, it is less expensive to have a backup bus available to support the schedule if there is any breakdown. However, it is quite different for a weekly aircraft schedule in which aircraft may leave the base for a long distance and long time. The maintenance requirement becomes a very important factor for aircraft scheduling because of considerations of safety, limited available maintenance away from the base and limited backup airplanes, etc.

2. Service frequency: The frequency of service is quite different between the airlines and urban public transportation systems. Because of the cost, the fare, the demand and operational constraints, it is impossible and unnecessary for the airlines to provide as many services on a route as those in urban public transportation systems. Besides, governments may restrict the number of services provided. In contrast, urban public transportation systems have to provide a large amount of services for the demand they face every day. High service frequencies increase the difficulty of producing the schedule[26]. This also increases the difficulty of applying (and developing) computer-based scheduling systems. Algorithms currently available often have a restriction on the size of problem which can be solved. If the problem is too large, the machine solution may not be satisfactory even if one can be obtained by simplifying or decomposing the problem.

3. Timetable Construction: In the urban public transportation scheduling process, the timetable is fixed for both vehicle and crew scheduling activities. However, this is not always true for the airlines. The timetable construction may be completed along with the aircraft scheduling process in the airlines.

As we know, both the transportation demand and fleet characteristics will affect (or restrict) the services provided. For urban transportation systems, we can follow the

[25] Of course, this concern is also affected by the safety factor. The safety requirements of a bus are not so strict as those of an aircraft.

[26] This does not imply that scheduling problems with lower service frequencies as in the airlines are easier that those in urban public transportation systems. Scheduling problems in the airlines still have to deal with a large number of flight legs and possible connections for the schedules.

transportation demand and set up the timetable directly with little concern about the fleet characteristics[27], since the vehicles or cars for a specific mode (bus) or a specific transit line in urban systems usually will not vary much. It is not difficult to find suitable vehicles to satisfy the timetable (the planned services).

However, this is totally different in the airline industry. The fleet characteristics are very important in planning services that a company can provide. They and other factors such as the away-from-base time, operating, capital cost and maintenance requirements will significantly restrict the availability of aircraft for desired schedules. These factors will have more influence on timetables and aircraft schedules in the airline industry than those in the urban transportation systems. Therefore, it is important that aircraft scheduling should be coordinated with the generation of timetables [3].

4. Competition: The nature of competition in the two fields is totally different. Most airlines are privately owned and competition between airlines is intense. However, many urban public transportation agencies are publicly or quasi-publicly owned. In many cities (especially in the United States), there is one agency serving large areas without any competition (except from other modes, notably the auto). Sometimes, this will decrease the perceived importance to agencies to produce efficient and cost-saving schedules or even to improve the schedules. Sometimes they can not afford to improve the schedules because of the budget or subsidy constraints.

5. Objective: There is a major difference between the objectives of the vehicle scheduling problem and the aircraft scheduling problem. Although both types of scheduling problem may aim to minimize the cost, the vehicle scheduling problem will usually emphasize the fleet size while the assignment of aircraft types is usually the first consideration for the aircraft scheduling problem.

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[27] The fleet characteristics include size, capacity, vehicle type, the limitations of functions of different vehicle type, etc.

The focus of the objective function may also be different between the two fields. For example, one objective in airline scheduling, as indicated by Elce [51], may be to maximize profit by including as many long-haul legs as possible to avoid extra costs resulting from frequent take-offs and landings [51]. In transit systems, these issues do not arise. In addition, long blocks may not be appropriate or necessary for a good transit schedule. Another difference is in the use of deadheading. In urban transportation systems, deadheading (either for vehicle or crew) may be a useful tool for solving scheduling problems because of its low cost. In contrast, deadheading an airplane is much more expensive and will not be used unless strictly necessary [32]. Nevertheless, air crew deadheading can sometimes help obtain a feasible crew schedule or may simply be more cost-effective.

6. Constraints: In general, aircraft and air crew scheduling will be concerned with operational restrictions and safety factors as well as union contract terms. Most urban crew scheduling, on the other hand, will focus on the union contract terms. Fewer safety requirements will be imposed from the authority or the government on urban crew schedules. Most vehicle scheduling methods do not take into account operational constraints. The available fleet size dominates the constraints in urban vehicle scheduling. Sometimes, other constraints such as a minimum layover time will be considered in vehicle scheduling. For crew scheduling, most constraints concern the platform time, spread hours, break time, pay penalties and allowances.

Aside from the differences mentioned above, joint vehicle/crew scheduling may also be particularly attractive for urban public transportation scheduling. The interactive effects between vehicle and crew scheduling have been addressed in some prior research [3][7][34][39], as will be discussed later in this section.

2.3.2 The Joint Vehicle/Crew Scheduling Problem

There is little dispute that aircraft scheduling should be performed prior to air crew scheduling. The capital investment is much higher than the crew cost in the airline industry, while this is not so in urban public transportation. It is reasonable for a planner to schedule first what can cause the largest cost impacts. Consequently, the combined aircraft and crew scheduling problem is not as necessary for airlines[28] as it may be for urban transportation authorities.

From the viewpoint of the formulation and the optimization solution, joint vehicle/crew scheduling may be a better strategy than the sequential process. But it has proved difficult to solve one NP-hard problem, let alone the combination of two NP-hard problems which this approach would imply. Due to the complexity of the joint scheduling process, most researchers would rather (or have to) separate the problems to have immediate yet acceptable results for the applications instead of being stuck in the joint scheduling problem. Nevertheless, there is still some research trying to explore the possible applications of the joint vehicle/crew scheduling problem. Two prior attempts use different ways to approach this problem: one developed by Ball et al. [34][47], and the other by Scott [7][39]. Ball et al. use one model to construct the crew schedule and the vehicle schedule. Scott imposes the cost information from the relaxed crew schedule onto the vehicle scheduling process to get a better vehicle schedule.

1. Scott's method:

Scott's algorithm does not really deal directly with the full complexity of the joint scheduling problem. Rather it tries to create a vehicle schedule that takes into account information on the related manpower cost. As Scott said, he wanted to *create vehicle*

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[28] Instead, the combined timetable/aircraft scheduling problem may be more practical for the airline industry. This problem could be formulated as a combined routing/scheduling problem as discussed in Bodin et al. [3].

schedules that are efficient in their use of manpower. He follows a strategy similar to the HASTUS crew scheduling program (HASTUS-Macro and HASTUS-Micro)[29] to establish his algorithm.

The algorithm consists of three steps. First, he uses a modified transshipment model to get an initial vehicle schedule based on a composite objective function which minimizes the fleet size, vehicle miles and platform time. The model is designed to be able to make more accurate trade-offs between deadheading, layovers and pull-ins (pull-outs). Second, the linear relaxation similar to HASTUS is employed to obtain the manpower information. The model is basically a crew scheduling model. One difference from the original linear relaxation formulation in HASTUS (HASTUS-Macro), is that the model employs a variable in the formulation instead of constants used in the model constraints. As Scott said, the use of this kind of variable can *introduce a variable vehicle schedule structure into the model.*

$$b_p = \sum_{(qr) \in B_P} y_{qr} , \quad p \in p \tag{2.10}$$

$$B_p = \left\{ (qr) \in B : \quad q \leq p \leq r \right\}$$

$$v_{qr} = y_{qr} \tag{2.11}$$

$$q_p = \sum_{(qr) \in B_{P'}} y_{qr} , \quad p \in p \tag{2.12}$$

$$B_{p'} = \left\{ (qr) \in B_p : \quad q = p \right\}$$

The variable, y_{qr}, indicates the service demand (the number of required vehicles) between two periods. He uses this variable to replace the constraint values on the left hand

[29] The HASTUS strategy will be discussed in the chapter 3.

side of (2.10), (2.11) and (2.12) above. In Scott's extended linear model, the new constraints will substitute for the old constraints in the HASTUS-Macro model (from (3.6) to (3.8)). The value of y_{qr} depends on the vehicle schedule. Different vehicle schedules from the first step can change the value of y_{qr} and therefore result in different crew schedules in the linear relaxation model.

The reason Scott uses this variable is that the manpower information available at this step will be used to improve the initial vehicle schedule solution obtained in the first step. The change of the vehicle solution will then change y_{qr} and hence change the manpower solution until the ideal solution is obtained. The employment of the variable is helpful for this iterative evaluation process.

With the initial vehicle schedule solution produced at the first step, the values of this kind of variable can be determined and the extended linear relaxation model can be solved. In addition to this, the initial solution can also help restrict the model's size.

Scott produces two crew schedules at this step: the crew schedule solution that fixes every y_{qr} consistent with the initial vehicle schedule, and the optimal crew schedule solution that just fixes b_p, i.e. it fixes the sum of y_{qr} at the initial solution level. The crew schedules generated here are thus the approximations of feasible schedules rather than real feasible schedules.

In the final step, a heuristic method is designed to improve the initial solution marginally with the information (solution and objective cost) from the second step of the model. The information is based on the comparison of every y_{qr} and the objective values of two solutions from the second step. Comparing the difference between y_{qr}, the initial vehicle schedule will be adjusted in accordance with y_{qr} from the optimal solution and go back to the second step. According to Scott, the iterative heuristic will stop only if a feasible vehicle solution that costs out optimally in the extended linear model is found, or if no alternative optimum more closely models the existing feasible solution and it is impossible to eliminate rejected vehicle schedules without creating others.

The algorithm was tested on two timetables from the Montreal transit agency with estimated crew cost saving of less 1%.

2. Ball et al. 's method:

There are two important features in their joint crew/vehicle scheduling algorithm [34][47]: (1) the use of so-called *d-trips* instead of trips as a basis for the analysis; (2) the crew schedules and the vehicle schedules can be obtained simultaneously instead of the vehicle scheduling being performed first in the sequential process.

Ball et al. argue that crew costs dominate vehicle costs in the urban transportation system, so they want to perform the crew scheduling and the vehicle scheduling concurrently. The algorithm can create both schedules at the same time. Nevertheless, they focus more on crew scheduling and the methods included in their algorithm mainly relate to crew scheduling. Actual methods or testing results are not available for the vehicle schedules. They just explain how it is possible to get the vehicle schedule along with the crew schedule.

Since crew costs will be greater than vehicle costs in urban transportation systems, they focus on only the crew scheduling problem initially. In the sequential scheduling process, trips, which start and end at terminals and/or garages, are the most important input to the vehicle scheduling. The crew scheduling has to have the information of blocks generated in vehicle scheduling and the information of potential relief points as the input to cut the blocks at relief points into pieces which are then matched into crew duties. That is why the relief point information is very important to crew scheduling. Crew scheduling can not use trips as the direct input because they are not able to provide this kind of information, so they introduce the concept of the *d-trip* in their model.

Ball et al. define a *d-trip* as the portion of a trip or the combination of trips that must be traversed by the same crew and vehicle. It is formed by breaking trips at their possible relief points, not just at stations or depots as in trips. In this way, they can provide the information of all possible relief points for crew scheduling and use *d-trips* as a direct input.

The basic logic of their algorithm is: original trips listed in the timetable now are broken into *d-trips*, i.e. each trip is covered by at least one *d-trip*. For the vehicle schedule, blocks were previously composed of trips whereas now, they are constructed from *d-trips*. For the crew schedule, crew duties can now be formed by directly matching d-trips. It does not have to generate blocks, which are then cut into pieces and matched into duties as in the sequential process. Therefore, the vehicle and crew schedule can both be built by *d-trips* at the same time.

The algorithm, which is designed to solve crew scheduling problems, is formulated as a set partitioning problem consisting of 3 levels: piece construction, piece improvement, and run generation. Each level will use some models or techniques, but matching is the main tool for these 3 steps.

At the first level, the algorithm tries to combine *d-trips* into different pieces of work[30]. During the combination (or matching) process, certain criteria such as minimum cost and maximum piece length should be obeyed. For the purpose of minimizing cost, they employed a cost function that consists of deadheading time, layover time, and total piece time. They use these criteria and cost function to group *d-trips* into different pieces.

At the second level, they try to improve all pieces obtained in the first step using an interchange heuristic for this resplitting and recombination process. As described in Ball et al.'s papers, in general, the method tries to combine two short pieces into a long piece, to combine and resplit a short piece and a long piece into two median-sized pieces, or to combine and resplit two short pieces and delete some *d-trips*. At the final stage, the pieces are combined into runs with a minimum cost matching technique.

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[30] A piece of work is a part of a crew duty as defined in Appendix A.

Vehicle schedules can be derived from the first two levels by inserting necessary connection trips, such as deadheads, pull-ins, and pull-outs, and combine them with d-trips into blocks, then vehicle schedules.

The algorithm was tested with data from the one division of the Baltimore MTA bus system. They produced a solution with a 1.5% reduction in total paid time or a 9% saving in variable pay time. The solution had more trippers and fewer 3-piece runs than the original one.

As Rousseau indicated [32], savings from these joint scheduling methods do not appear to be significant. Researchers would rather focus on the separate scheduling problems that can produce equivalent savings with less complicated methods (better cost-performance ratio). After these two algorithms, there has been no other published work on the joint scheduling problem. Unless computer technologies improve further and/or new models and algorithms appear, the joint scheduling approach is unlikely to replace the sequential scheduling process in the near future in the transit industry.

Chapter 3: Computer-based Scheduling in Urban Public Transportation

Manual vehicle and crew scheduling require many schedulers due to the complexity of the problems. The production cycle of a set of manual vehicle and crew schedules is typically lengthy, partly because of the large amount of paperwork involved. The long and expensive time to produce manual schedules may make it difficult to change the required service level in response to demand shifts, but it also lacks the ability to do sensitivity analysis that might be used to evaluate potential changes in service or contract terms. The application of computers in the scheduling process may well be able to deal with these problems more effectively. In this chapter, the evolution of computer-based scheduling in the last several decades is first discussed. Then, two representative scheduling packages: RUCUS and HASTUS are presented in more detail with several other packages also introduced more briefly.

3.1 Evolution of Computer-based Scheduling

In 1954, Dantzig and Fulkerson [65] presented a linear programming problem that started the following fruitful investigation of the scheduling problem. The University of Leeds began research on the application of computers to transportation scheduling problems several years later [64]. Around that time, several research projects also tried to employ computers to solve scheduling problems [61][64]. Before 1970, however, due both to limitations of computer technology and a lack of suitable algorithms and computer codes, no satisfactory computer-based scheduling applications had been demonstrated.

However at about this time, many transportation agencies, authorities and researchers started to be aware of the importance and potential benefits of computer scheduling and began to devote more serious efforts to the development and application of computer-based scheduling tools. After 1970, many different heuristic procedures, models[1] and algorithms were experimented with. Several of these computer systems represented significant breakthroughs and resulted in applicable and useful tools that were able to tackle real bus scheduling problems in some urban public transportation agencies. Some of these systems were designed specially for bus scheduling, such as AUTOBUS [48]. Some were developed as complete systems that were able to perform the whole sequential scheduling process including both vehicle and crew scheduling, such as RUCUS [68][69][70][78] and HASTUS [18][24][49][60] in North America.

In examining these systems, significant difference can be seen in the way both software developers and schedulers approached computer-based scheduling tools before and after about 1980. Before this time, most packages had restrictions that made them difficult to use as flexible tools. As a result it was usually difficult to use them to produce acceptable and competitive schedules (compared with manual schedules) for different authorities. These restrictions derived from the complexity and variability of work rules and practices in different authorities. The available technology and algorithms were not capable of dealing with the full complexity of work rules and practices at different authorities. These packages could provide acceptable schedules only for some authorities with similar characteristics and work rules.

After this time, in order to make programs more flexible and useful to different users, developers became more inclined to facilitate human intervention as part of the

[1] Most of models employed at that time were assignment models or the set covering models.

computer procedures. With the possible interaction between the scheduler and the machine, schedulers were able to become much more highly involved in the problem-solving process. Therefore, experienced schedulers could use their knowledge, experience and preferences for specific types of schedules, to guide, evaluate, and adjust the inputs or results of models during the scheduling process. For example, schedulers are highly knowledgeable about route structures, operating conditions, and potential variances of running times. They often have a clear idea about what a suitable schedule for the authority should be like. Therefore, they can make better adjustments and decisions about the intermediate results, restrictions and parameters inside the program to help generate a set of more satisfying and feasible final schedules. As Stern and Ceder [37] said, the interactive approaches will make schedulers more confident in the results and avoid the errors of "*one-pass*" computer procedures.

The development of RUCUS is a good illustration of this evolution. The first generation of RUCUS was a non-interactive system that was developed in the early 70's and received considerable application interest. As a result of user concerns and criticisms, the next generation of these software begun in the late 70's became a much more interactive system.

Other improvements include greater control over the final results and the employment of computer graphics. Greater control over the final results is very important for schedulers in obtaining an acceptable solution. Even though more human intervention is allowed in the newer computer procedures, the final solution generated by the computer system may still be unsuitable for direct application. If schedulers can have more control over the final result, a more feasible and acceptable schedule may be made available requiring minimal adjustments from the final computer solution. For example, HASTUS allows interactive modifications through the computer system after the generation of the automated result. If the final automated result is not acceptable, schedulers can usually use the interactive function to "massage" this solution into an acceptable schedule.

Computer graphics is also a helpful new tool for a computer-aided scheduling system. Since computer technology has been advancing rapidly, more powerful hardware (PC, the work station and the mouse) and graphics software have been developing. The progress makes the employment of computer graphics inexpensive and practical for computer-aided scheduling tools Computer graphics can help the computer-aided scheduling system because more friendly for users. For example, data entry and error-checking can be easier and clearer through graphical display and can result in fewer errors. Graphical display can also help present the computer result in a much clearer way and can greatly facilitate interactive scheduling. Finally the easier use of the computer system can shorten the training period for new schedulers.

3.2 RUCUS & RUCUS II

The Run Cutting and Vehicle Scheduling (RUCUS) computer system [68][69][70] was developed under the sponsorship of the Urban Mass Transportation Authority (UMTA) of the United States in the early 1970's and was released to the transit industry in 1975. RUCUS, a non-interactive (batch mode) package, is one of the first complete scheduling packages[2] [73] in the world to receive substantial application in the transit industry.

RUCUS was explicitly designed to mimic the manual scheduling process so as to increase the likelihood of acceptance by schedulers after failure of earlier systems. It contained three components: TRIPS, BLOCKS, and RUNS. TRIPS produced headway sheets based on the transportation demand. These headway sheets then were used to construct the timetable of all revenue trips. BLOCKS was the vehicle scheduling program

[2] The complete package here means that the system consists of both vehicle and crew scheduling subsystems

which took into account the TRIPS output (timetable) as well as other constraints, such as spatial and operational constraints, and generated vehicle blocks. The vehicle schedule consisted of these blocks. RUNS was a run cutting program that produced the crew schedule based on the blocks generated in BLOCKS.

BLOCKS [69][70] employed a minimal cost flow model, which is almost identical to the VSP model introduced in section 2.2.4 (equations (2.1) to (2.4)), to produce vehicle blocks with minimum cost. The model formulates the problem as a cyclic network as introduced in *figure 2-3 (b)* and section 2.2.2. The back flow arc deals with the fleet size constraint as well as the additional cost every time a vehicle begins service. Each pair of nodes, which is connected by a revenue-trip arc, represents the start time and location, with the end time and location for a specific trip. A cyclic path starts from the bottom node (garage), follows the back flow arc (the capital-cost arc), goes through pull-out arc, and tries to combine revenue-trip arcs and deadheading arcs without violating spatial, time, and other constraints, then returns to the bottom node (pull-in arc). Each cyclic path represents one feasible block. As described in chapter 2, the costs associated with all kinds of arcs and the fleet size will significantly influence the solution. Theoretically, each revenue trip must be covered by a block (path) exactly once at minimum cost. This minimum cost flow model is solved by the out-of-kilter algorithm [69]. BLOCKS was restricted to deal with one type of vehicle, and all vehicles had to come from a single garage.

RUNS [68][70] was used to assign drivers to cover the vehicle schedule. and employed a two-step heuristic procedure. The procedure first generates an initial schedule based on blocks from BLOCKS and the initial solution is the refined by eliminating trippers and reducing the cost. There are five phases in RUNS: (1) data processing; (2) generation of the initial solution; (3) elimination of trippers; (4) run cost minimization; (5) production of the report. The first four phases could also be used as independent functions for evaluation purposes, i.e. each phase could be executed or terminated independently.

Data processing needed three kinds of data: parameters that specified work rules, other constraints and options for desired runs; vehicle blocks; and travel times between relief points. The second phase generates an initial crew schedule consisting of one-piece and two-piece runs that satisfy the work rules. However not all blocks could be cut and combined into these legal runs, thus some trippers were usually inevitable. By changing various parameters, the block-splitting could be executed repeatedly to seek a more satisfactory initial solution. The third phase tried to eliminate as many trippers generated in the initial solution as possible without violating work rules. This procedure would be stopped either when all trippers had been eliminated, or no further elimination was possible. In the fourth phase, the function tried to reduce the total pay-hour cost of the solution previously generated while respecting work rules. This function would be stopped when no more savings were possible.

After run cost minimization, there was another optional phase before the final schedule is reported in the fifth phase. This additional phase eliminated trippers regardless of work rules or other constraints. Then, the new schedule would go back to the fourth phase to try to massage all runs into legal runs.

Table 3-1: Comparison of RUCUS and the Manual Vehicle Schedule

	MBTA Manual	**RUCUS BLOCKS**	**Saving**
Revenue Hour	743.5	742.1	**-0.1%**
Layover & Deadhead	269.3	276.4	**+2.5%**
Total platform hour	1012.8	1018.5	**+0.6%**
No. of Vehicle Blocks	158	151	**-4.6%**

According to Wilson [78], RUCUS was once adopted by around 33 transit authorities with fleet sizes ranging from 75 to 1000. Reported driver pay savings ranged from 0% to 8% for 15 authorities. One specific evaluation of RUCUS (both vehicle and crew scheduling) occurred in one garage of the MBTA (Boston) [70] in the mid 1970's. The test compared the RUCUS vehicle and crew schedules with the manual schedules, with the results shown in *Table 3-1*. As shown in *Table 3-1*, no saving resulted in the vehicle scheduling process. However, as shown in *Table 3-2* some significant savings were achieved by the crew scheduling element of RUCUS in terms of the number of drivers, platform times, etc. Goeddel [70] thought that RUCUS could produce reliable and cost-efficient vehicle and crew schedules for a large transit system. However, despite these apparently promising test results in the MBTA, RUCUS was never implemented at the MBTA, for reasons which are not known.

Table 3-2: Comparison of RUCUS and the Manual Crew Schedule

	MBTA Manual	**RUCUS Blocks**	**Saving**
Platform Hours	1119.3	1018.5	**-9.01%**
Spreadover Hours	1523.8	1442.4	**-5.34%**
Total Pay Hours	1293.4	1240.8	**-4.07%**
Total Runs	144	142	**-1.39%**

Several deficiencies about RUCUS were described by Wilson [78] as follows: (1) It is difficult to use because it is not scheduler-oriented. (2) The data base management is inefficient. (3) The reporting capabilities are limited and the documentation is poor. (4) It lacks feedback between the planning, scheduling, and run-cutting procedures. While RUCUS was widely implemented, it was not viewed as a completely successful attempt to develop an automated scheduling system.

RUCUS was substantially and fundamentally revised to form RUCUS II in the early 1980's (started in late 70's). As Luedtke indicated [73], RUCUS II was designed to overcome deficiencies in the design and usability of RUCUS. Taking advantage of more advanced computer technology, RUCUS II was an interactive, and much more user-friendly system. For example, either a totally interactive procedure or automated techniques were available for the vehicle scheduling procedure. It also contained more optional functions. For example, three options based on headway, layover or passing times at the maximum load point, could be selected as the basis for building trip schedules.

Some improvements in the vehicle scheduling function were also made in RUCUS II. Unlike the vehicle scheduling function in RUCUS which could only deal with the one-garage vehicle scheduling problem, the multiple-depot vehicle scheduling problem (VSPMD) could be solved in RUCUS II. It first generated all blocks as a one-depot problem, then assign these blocks to different depots [73].

There are several important characteristics of the driver run-cutting subsystem in RUCUS II. First, it allows improved user flexibility and control while generating and modifying the assignments of driver runs. Second, the assignments of driver runs (1-piece, 2-piece, and 3-piece) can be done either by the manual interactive scheduling procedure or the automated scheduling procedure. Third, the user specified cost function which includes work rules, pay hour cost provisions, and desirable constraints is used for the generation (or evaluation) of runs. Fourth, the heuristic optimization function can be used to reduce the make-up times, the overtime penalty, and other premiums. Fifth, the final run-cutting results are reported with graphic displays [78].

3.3 HASTUS

HASTUS is an extensively applied crew scheduling program that has been widely reported in the literature [18][19][21][22][23][24][28][32][49][60][74]. As mentioned in Chapter 1, HASTUS is developed by the Transportation Research Center of the University of Montreal and GIRO Inc.. Rousseau and Blais [18] described HASTUS as an *intelligent-interactive* system because of its use of mathematical optimization tools and the high level of human intervention possible during application of the software.

Basically, HASTUS consists of three subsystems[3]: HASTUS-Bus vehicle scheduling subsystem, HASTUS-Macro approximate run-cutting and cost estimating subsystem, and HASTUS-Micro crew scheduling subsystem. HASTUS-Bus is an interactive vehicle scheduling tool based on specified service demands. HASTUS-Micro is also an interactive tool which produces the detailed feasible crew schedule with an associated exact cost. HASTUS-Macro is a rather special and unusual element among all computer scheduling packages. As Rousseau states [32], it is designed to solve a relaxation of the driver scheduling problem on a modified (simplified) vehicle schedule. It can be used by itself as a cost estimation model and it also acts as a preprocessor for HASTUS-Micro. In the latter case, the HASTUS-Macro solution is used to guide the HASTUS-Micro run cut. As Smith and Wren [28] described, the work of these three subsystems is to use mathematical programming methods to produce a set of theoretical duties to match the overall profile of the bus schedule, and then derive a realistic set of duties using this as a guide.

HASTUS-Macro, which was the first subsystem developed in HASTUS (in 1977), can also be used to estimate the potential cost impacts from the modifications of work rules or other changes such as the service level. It focuses on the generation of certain limited types of duties to obtain a reasonable estimate of the cost rather than on obtaining a set of feasible crew schedules. To this end, it simplifies the vehicle schedule and relaxes various conditions[4] to get an approximate yet representative solution without requiring too much computation. Consequently, it can serve as a useful tool to quantify the impact of possible changes during contract negotiation or the evaluation of some operational or service changes. HASTUS-Micro and HASTUS-Macro collectively constitute a complete

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[3] The components of the system are described in Rousseau and Blais [18].

[4] These simplified conditions are discussed below.

crew scheduling algorithm. Lessard et al. [24], Rousseau [32], Rousseau et al. [49], have presented detailed descriptions of this bus driver scheduling (BDS) algorithm. The general crew scheduling model is presented below.

The General Crew Scheduling Model of HASTUS [24][49][60]:

$$Min \quad \sum_{(ij,mn)\in D} c_{ij,mn}\, x_{ij,mn} \tag{3.1}$$

St.

$$\sum_{i\in T_p} y^{p}{}_{ik} - \sum_{j\in T_p} y^{p}{}_{kj} = b^{p}_{k} \tag{3.2}$$

$$\sum_{(ij)\in D(i,j)} x_{ij,mn} - y^{p}{}_{ij} = 0 \tag{3.3}$$

$$BX \geq q \tag{3.4}$$

$$x_{ij,mn} \geq 0 \text{ and integer}$$

$$b^{p}_{k} = \begin{cases} -1 & \text{if } k \text{ is the starting time of block } p \\ +1 & \text{if } k \text{ is the ending time of block } p \\ 0 & \text{otherwise} \end{cases}$$

$$y^{p}{}_{ij} : \begin{cases} 1 & \text{if piece}(i, j) \text{ which is included in the block } p \\ & \text{is used as part of a driver run.} \\ 0 & \text{otherwise} \end{cases}$$

D : *the set of feasible duties*

$D(i, j)$: *the set of feasible duties with one piece of work (i, j)*

To simplify the presentation, all the papers regarding HASTUS above were used to assume that every duty included at most 2 piece of work: one piece is represented as (i, j) here, and the other is (m, n). $x_{ij,mn}$ is a binary variable which equals 1 if an operator is assigned to the duty including (i, j) and (m, n). $c_{ij,mn}$ is the cost of this duty. T_p is the set of times k which represents the relief times, the starting time, or the ending time for the block p.

Constraint (3.2) is used to partition each vehicle block into pieces of work. For example, if a block (Block p) lasts from 9:00 to 13:00 and k represents the only relief time during this block at 11:00, then $b^p_{(11:00)}$ equals 0. Therefore, the block can be partitioned into two pieces of work: one piece is from 9:00 to 11:00, i.e. $y^p_{(9:00,\ 11:00)} = 1$; and the other one is from 11:00 to 13:00, i.e. $y^p_{(11:00,\ 13:00)} = 1$. If b^p_k does not equal 0 (i.e. k represents the starting time (9:00) or the ending time (13:00)), the block can be either partitioned into multiple pieces of work (depending on allowed relief points during this block), or kept as a single piece.

Constraint (3.3) makes sure that the feasible pieces[5] partitioned in Constraint (3.2) are used to constitute workdays. For example, if $y^p_{(9:00,\ 11:00)} = 1$, it may be assigned to a two-piece run as a part of the duty, i.e. either $x_{((9:00,\ 11:00),\ (m,\ n))}$ or $x_{((m,n),\ (9:00,\ 11:00))}$ will be equal to 1 as well.

Constraint (3.4) refers to other constraints such as work rules. The pieces of work cut in Constraint (3.2) and the duties matched in Constraint (3.3) have to abide by the work rules defined in Constraint (3.4), such as the minimum piece length of 2 hours.

This general model alone is unable to deal with the large transit crew scheduling problems. Therefore, the model is decomposed into three parts with the solution strategies as summarized below[6].

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[5] A "feasible piece" implies that certain rules, such as minimum and maximum piece lengths are satisfied.

[6] To make the presentation easier, a crew run is limited to at most two pieces of work as above.

Step 1: The HASTUS-Macro Relaxed Model

First, HASTUS-Macro will be executed to provide the information (types of pieces of work and the number of pieces) need by the heuristic procedure used in the next step. Because HASTUS-Macro is designed to provide an approximate solution for the real feasible crew schedule, it simplifies the problem in the following key areas:

(1) The integral constraint on the variables representing the number of duties of a certain type is relaxed.

(2) The starting time, relief time and ending time for all blocks and pieces of work can only occur at predetermined times.

(3) The workdays selected must be sufficient to cover the total requirement of drivers per period instead of requiring that they exactly cover each block individually.

As Rousseau said [32]: *It retains the essentials of the bus schedule structure and its impact on the contract rules and costs without retaining the precise bus schedule.* The relaxed problem[7] is formulated as follows:

$$Min \sum_{(ij,mn)\in D} c_{ij,mn}\, x_{ij,mn} \qquad (3.5)$$

$$\sum_{(ij,mn)\in D_P} x_{ij,mn} \geq b_p, \qquad p \in P : \text{a set of periods} \qquad (3.6)$$

$$D_p = \{(ij,mn) \in D;\ (ij,mn) : i \leq p \leq j \ \ or \ \ m \leq p \leq n\}$$

$$\sum_{(ij,mn)\in D_{p'}} x_{ij,mn} \geq v_{qr} \qquad (3.7)$$

$$D_{qr} = \{(ij,mn) \in D :\ (ij) = (qr) \ or \ (mn) = (qr)\}$$

[7] Scott [7] extends this formulation to perform his joint scheduling analysis as mentioned in section 2.4.

$$\sum_{(ij,mn) \in D_{p'}} x_{ij,mn} \geq q_p, \qquad p \in p \tag{3.8}$$

$$D_{p'} = \{(ij,mn) \in D : i = p \text{ or } m = p\}$$

The first constraint (3.6) ensures that the number of drivers assigned in any period is not less than the number of vehicles required (b_p) in that period. The second constraint (3.7) prohibits the partition of small blocks. It requires that the number of pieces of work from q to r is at least as large as V_{qr}, the number of small blocks from q to r. A small block is the a block (defined by schedulers) that cannot be partitioned and should be assigned as one piece of work to a driver [24]. This constraint indicates that the existence of these small blocks should be allowed during the required manpower estimating process (this Macro crew scheduling process) [39]. Constraint (3.8) requires that the number of pieces of work is at least equal to the number of pull-out blocks (q_p) for that period. This constraint is to guarantee that the given vehicle block starting times are respected during the crew scheduling process [39].

Step 2: Partitioning

The Macro crew schedule generated in the first step is used to help create the initial feasible solution in the following two steps. To create the initial feasible solution, partitioning is first performed to cut the blocks.

A heuristic procedure replaces the partitioning formulation of Constraint (3.2). It cuts blocks into pieces of work according to the optimal relaxed solution from Macro (Step 1). The Macro simplified crew schedule provides information on the number of pieces of work of each type required. The partitioning formulation (and the associated heuristic procedure) follows the information and tries to cut the blocks into pieces of work that are as close as possible to those specified in Macro.

Step 3: Matching and Marginal Improvement Procedure

After the blocks have been cut into pieces, an assignment algorithm, which replaces Constraint (3.3), is employed to match pieces of work generated at the second step into initial crew duties. Finally, a marginal improvement algorithm is employed to improve the solution by re-partitioning the blocks and eliminating as many trippers as possible. This improvement algorithm is the *optimization* function used in the evaluations in Chapter 4.

HASTUS is quite flexible in taking into account different work rules in the computational procedures. Schedulers can define most desired work rules as restrictions in the program. They can also impose other parameters to induce the program to approximate certain desired duties[8]. HASTUS also provides a fully interactive environment for schedulers to cut blocks.

Beyond the three basic functions mentioned above, there are also some extensions and new functions added in the system. For example, a new crew scheduling subsystem, CREW-OPT, has been developed using column generation techniques to deal with crew scheduling problems with restricted sizes in a more efficient and effective way. Other vehicle scheduling tools, such as HASTUS-Minbus, are also available in the HASTUS system.

Seguin and Hamer [59] reported that crew cost savings of 1% to 6% have been obtained from applying HASTUS at dozens of transit authorities around the world. Another paper indicated that HASTUS made possible an annual saving of $4 million for the S.T.C.U.M (Montreal) [60]. The savings result from vehicle scheduling are also reported by Koffman and Rousseau [81] as mentioned in Chapter 2. For example, bus savings of about 7% and saving in annual cost of $3 million were reported from the installation of HASTUS-Minbus at the Ottawa-Carleton Regional Transit Commission

[8] This is presented in detail in Chapter 4 in this thesis.

(OC Transpo). HASTUS is certainly representative of the current generation of computer crew scheduling packages.

We will discuss the characteristics of HASTUS further and the experiences of the application of HASTUS in the MBTA (Boston) in chapter 4.

3.4 Other Scheduling Tools

There are many other automated scheduling systems, some of which will be mentioned briefly in this section. AUTOBUS is a graphic man-machine interactive program that is especially designed for bus scheduling. The system is based on the deficit function algorithm proposed by Stern and Ceder [37]. Ceder and Stern describe AUTOBUS from the construction of timetables to bus scheduling in their paper [48].

Two other computerized bus scheduling programs are VAMPIRES and TASC as discussed in Smith and Wren [38] and Hartley and Wren [46]. VAMPIRES and TASC are also included as a subsystems in BUSMAN. VAMPIRES, which was developed in the late sixties and used in the early seventies, is a network-based bus scheduling program. It was designed to deal with vehicle scheduling for a mixture of regular public services and special services (like school buses) across the network. It allows vehicles to switch between different services and to interline. It can also show the savings possible by the retiming of services (trips). Several empirical cases using this system are presented in Smith and Wren's paper [38]. TASC [44][46], which was used in late seventies, is more a route-based program used to plan and schedule regular services along a single route or related routes. Timetables can also be produced before scheduling. It is easier and quicker to use than VAMPIRES. The savings in numbers of vehicles required was reported to range from five percent to as much as 20%-24%. As Hartley and Wren [46] said: TASC is designed to be used for day-to-day scheduling, whereas VAMPIRE would normally be used when a major service has to be revised (maybe once a year).

BUSMAN is a large transit-oriented computer system developed in the U.K. Not only is it able to deal with vehicle scheduling and crew scheduling, but it also provides functions to help in marketing, planning and administration tasks. Williamson [80] has a detailed introduction to it in the third workshop.

There are many other computer systems that have been developed and applied in different areas around the world, e.g. the HOT system in Germany. It has become a clear trend to use computer-based scheduling packages as a transportation management tool to help deal with the complexity of transportation scheduling problems and obtain the maximum benefits for both the authorities and the public.

Chapter 4: Computer-based Scheduling at the MBTA

This chapter focuses on the evaluation of HASTUS crew scheduling functions in the MBTA context. The impacts of HASTUS on the MBTA after its installation are discussed first. Then, possible future impacts are discussed, illustrated by applications of HASTUS-Micro and HASTUS-Macro to the MBTA. The first part of the evaluation focuses on the ability of HASTUS-Micro to produce acceptable automated crew schedules for a large (Cabot Garage) and a small bus garage (Albany Garage). The consistency between Macro schedules and corresponding Micro schedules are also addressed. The relationship between different part-time operator wage rates and constraints, and the resulting HASTUS-Micro automated crew schedules is examined for both garages. The relationship between the Macro files with different period lengths and their Micro schedules is then discussed.

The second part of the evaluation performs sensitivity analyses on both Macro and Micro. The possible impacts that different scenarios can have on the Macro schedules and final automated crew schedules (Micro schedules) derived from the first part of the evaluation are explored. First, different input files, including parameter files, selection files, cutting files, and Macro files are tested to see how they affect the final automated crew schedules. Second, different key parameters within Macro files are examined. Third, certain soft rules are relaxed to examine the impacts on Macro and Micro schedules for Cabot Garage, and to examine if an acceptable automated crew schedule can be found for Cabot. Finally radically, different work rules are examined at Albany Garage to assess their impacts on Macro and Micro schedules. The ability of the Macro solution cost to approximate the true Micro schedules cost is of particular interest in this set of experiments.

4.1 HASTUS in the MBTA

4.1.1 Background

The Massachusetts Bay Transportation Authority (MBTA) is an urban public transit system which provides bus, trolley and rail transit services to 78 communities in the Metropolitan Boston area with a total population of more than two and a half million [75]. It also serves (selectively) 52 communities outside the area with an additional population of over one and a half million. As shown in *Table 4-1*, the MBTA operates 4 rail transit lines (red, orange, green, and blue[1]) with a fleet size of 638 vehicles. Its bus system includes 9 garages (including one trackless trolley bus garage) with a total fleet size of 1047 vehicles serving 155 routes.

Table 4-1: MBTA Fleet Size*

	Fleet Size	A.M. Peak Vehicle	P.M. Peak Vehicle
Rail transit	638	447	451
Bus**	1047	773	684
Total System	1685	1220	1135

* According to 1994 winter schedule.
** Also including the trackless trolley system.

Four types of seasonal schedules for bus garages and transit lines have to be generated each year in the MBTA: the spring, summer, fall, and winter schedules (both vehicle and crew). The differences between these schedules result from changes in routes,

[1] The red, orange, and blue lines are heavy rail lines. The green line is a light rail line, and is sometimes called the street-car system.

service frequencies, the associated running times, recovery times, and relief opportunities. The service frequencies do not typically vary much between the spring, fall, and winter schedules but there is more difference in the summer schedule because of the lack of school trips. These schedules are produced by the Plans and Schedules Department in the MBTA which is responsible for all the timetables, vehicle schedules, crew schedules, and associated reports for the rail and bus systems. For each seasonal timetable, three or four different daily schedules are produced: weekday, Saturday, Sunday, and holiday schedules. Different demands (the number of trips) and different union contract terms (shown in *Appendix B*) result in these different schedules.

The process of introducing HASTUS into the MBTA was completed in 1986. The installation at the MBTA including both vehicle scheduling and crew scheduling subsystems (as presented in Chapter 3) was a fairly early version of HASTUS. For example, graphical scheduling, HASTUS-Minbus, or CREW-OPT are not included in the MBTA computer system. The current scheduling staff (most are crew schedulers), who are mostly computer-oriented, were recruited four years ago to replace the retiring manual schedulers, and to take greater advantage of the features of HASTUS. For the vehicle scheduling process in the Department, most of previous manual vehicle scheduling activities have been replaced and are now performed by HASTUS. The situation is somewhat different however for crew scheduling. Since crew scheduling is much more complex than vehicle scheduling and these schedulers had to learn about crew scheduling from the very beginning, it takes roughly 3 years for a crew scheduler to develop a good understanding of the complete manual crew scheduling process and knowledge[2] about the related scheduling areas. Only then can they become qualified schedulers who can operate independently with minimum supervision.

[2] The characteristics of garages, transit lines and bus routes, such as the travel times, route conditions, etc.

There has not been sufficient time for the scheduling staff to be thoroughly trained in the HASTUS crew scheduling subsystem. As a result the crew scheduling subsystem in HASTUS (Micro) is currently used only as a fully interactive tool (in the interactive mode) in the Department. The automatic crew scheduling function (the batch mode) has not yet been used in the regular scheduling process.

4.1.2 Impacts of the Installation of HASTUS at the MBTA

Although the automatic crew scheduling function has not yet been used at the MBTA and there has been no formal evaluation of the impacts of the installation of HASTUS, several impacts can readily be identified. First, the size of the scheduling staff has been reduced substantially from around 10 to 6 at the current time. Despite this reduction in staff, the department can produce more schedules than before in a particular production cycle. For example, prior to HASTUS 10 schedulers could produce 20 schedules (2 schedules for each scheduler) in a period of two to three weeks. With the help of the HASTUS interactive function, six schedulers are now able to produce 42 schedules in essentially the same time (in fall 1994). This represents a significant increase in scheduler productivity.

Second, the resulting schedules are more accurate because of the reduction in manually produced paperwork. With HASTUS, the computer system can help avoid errors during the scheduling process. In the past, some common errors, such as misplaced pieces of work, using a piece twice in different duties, or calculation errors (travel time, piece-length, duty-length, or cost), often wasted a tremendous amount of the schedulers' time and effort. Because of this increase in scheduling efficiency, HASTUS can also enable schedulers to try different scenarios (for cutting blocks or combining pieces into runs) to produce more economical schedules.

Third, the computer system can now provide more useful information faster not only for the Plans and Schedules Department, but also for other MBTA departments. The

MBTA now provides over 75 reports which are directly generated by, or interfaced with HASTUS. It gives the Plans and Schedules Department as well as other departments a clearer picture of the current operating plans. This information can be used to assist in supervision (or adjustment) of operations (or policies). For example, the Plans and Schedules Department is now able to provide a *Schsta (Schedule Statistics Report) Report*, which contains information on the total daily vehicle hours and vehicle miles for each route, for the revenue department and the real estate department. The department is also able to provide the Operations Planning Department *the Rectigraphs Report* which lists all duties and the relevant drivers' names in a much faster way. In the past, this report (the crew duties) was first generated in the Planning and Schedules Department, and was then distributed to the garages to be picked by the drivers. After the pick process[3] was finished, the complete report could finally be delivered to the Operations Planning Department. Now through the connection of the computers between the garages and the two departments (the Plans and Schedules Department and the Operations Planning Department), the Operations Planning Department can receive this report much more quickly.

To explore the feasibility and the possible impacts of using the automatic crew scheduling techniques in the MBTA context, the results of the evaluation with HASTUS are reported in the following sections of this chapter.

4.1.3 Depots Selected for Evaluation

The MBTA bus system was chosen as the case study for several reasons. First, the bus system is important in the MBTA because it provides more than half (see *Table 4-2*) of the total MBTA vehicle trips and vehicle miles, and its coverage is much wider that of

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[3] After crew schedules are finished by the Plans and Schedules Department, they are sent to the corresponding garages. The garages display these schedules and operators pick their desired duties in order of seniority.

the rail transit lines. Second, the characteristics (or conditions) of the bus system are much more diverse and complicated for scheduling than the rail transit system. In terms of crew scheduling specifically, the possible swings at different relief points and the relevant travel times complicate the development of crew runs more than for the rail system.

Table 4-2: MBTA Vehicle-trips and Vehicle-miles

	Vehicle Trips	Vehicle Miles
Bus garage: Cabot	498,630 (23%)*	4,919,916 (19%)*
Bus garage: Albany	151,306 (7%)*	2,623,213 (10%)*
Bus (total)	2,160,553 (63%)**	25,587,672 (51%)**
Total System	3,417,728	49,786,272

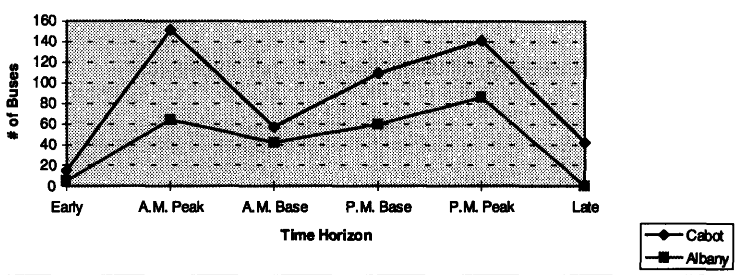
* Compared with the whole bus system (the third row of this table) for fiscal year 1993.
** Compared with total system (the fourth row of this table) for fiscal year 1993.

Two garages in the bus system were selected for the evaluation: Cabot Garage and Albany Garage. Cabot Garage is one of the largest garages in the MBTA system and includes about 23% of the total bus trips and 19% of the total bus miles (see *Table 4-2*). Albany Garage is one of the smaller garages and includes around 7% of the total bus trips and 10% of the total bus miles. With these two garages, we can not only assess HASTUS ability to deal with both simple and more complicated cases, but we can also make a comparison between these cases which have different degrees of complexity.

Since we want to test the potential of the HASTUS automated crew scheduling function in the MBTA context, instead of the comprehensive evaluation for all types of schedules, only the weekday schedule used in fall 1994 is chosen for this evaluation. The fall 1994 schedule reflects the latest operating characteristics (demand, route conditions, etc.) in the area as well as current MBTA characteristics (the union contract, numbers of full-time and part-time operators, etc.). Thus, the comparison between this schedule and alternative test schedules should be both realistic and representative.

Table 4-3: Base Run Cut (Fall 1994)

	Early	A.M. Peak	A.M. Base	P.M. Base	P.M. Peak	Late	FTO	PTO
Period*	Before 5:00	6:30 - 9:30	9:30 - 12:30	12:30 - 15:30	15:30 -19:30	After 21:00		
Cabot	15	151	57	109	141	42	182	56
Albany	5	64	42	60	86	0	85	45



Early : # of buses which start before 5:00 a.m.
Peak : # of buses in peak hours.
Base : # of buses in off-peak hours.
Late : # of buses in late hours, after 9:00 p.m..
FTO : # of Full-time operators
PTO : # of Part-time operators

* The approximate periods.

Table 4-3 shows some general statistics for the fall schedule at both garages. Except for the obvious differences in fleet size and manpower, there are several other differences between these two garages. First, no street reliefs are allowed in Albany Garage while there is no such restriction for Cabot Garage. Second, the last Albany duty ends before 9:00 p.m., while the last Cabot duty ends between 1:00 and 2:00 a.m.. Because of the more balanced distribution of work over the entire day, it is much easier for most duties in Albany Garage to be formed as two-piece duties[4]. In general, a two-piece duty is a better duty type for schedulers. For schedulers, a two-piece duty can cover at least one peak period (or even two peak periods) and satisfy general work rules in an easier and more economical way. Third, part-time duties in Albany Garage are a greater percentage of total runs than in Cabot Garage. As mentioned in Section 2.2.5, part-time duties are very helpful to cover leftover pieces of work which are not easy to be assigned into full-time duties. Since many pieces of work of this kind are usually generated during the run-cutting process, more allowed part-time duties will make the scheduling problem easier. According to *Table 4-3*, part-time duties amount to 35% of total required manpower for Albany Garage and only 24% for Cabot Garage. These differences make the crew scheduling process in Albany Garage much easier than in Cabot Garage.

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[4] Schedulers do not have to worry about how to assign pieces of work in the late period with the restricted manpower, overtime, and duty length constraints.

4.2 HASTUS Files Used for the Evaluation

There are two ways in which the crew scheduling subsystem of HASTUS (HASTUS-Micro) can be used: the interactive mode and the batch (or automatic) mode. The interactive mode allows interaction between the machine and the scheduler. After the vehicle schedule is available, a scheduler can cut the blocks piece by piece, and try to match them to form a complete feasible crew schedule as he used to do in the manual scheduling process. Instead of writing (or drawing) tremendous amounts of paperwork by hand as before, HASTUS takes over all the tedious and time-consuming paperwork and clerical functions traditionally done by hand. For example, in the past, schedulers had to write down every piece of work, and combine them into duties. They also had to calculate the travel times, length of pieces or duties, and cost totally by hand and by visual inspection during the cutting and matching process. With HASTUS, by using various commands, the machine can cut and combine the blocks according to the schedulers decisions. The machine takes care of all calculations and all clerical work. It also prevents any piece of work being used more than once, a mistake which can happen easily in the manual scheduling process.

Schedulers can also build various files necessary for the automatic crew scheduling function and modify these files in the interactive mode. Five major types of input files are necessary for the batch mode: the assignment file, the parameter file, the selection file, the cutting file[5], and the Macro file as shown in *Appendix C*. After the construction (or modification) of these files, the batch mode allows a scheduler to execute the automatic crew scheduling function (described in Chapter 3) as a one-pass procedure to produce the

[5] Rousseau and Blais [18] describe HASTUS and the relevant working files.

final schedule. HASTUS-Macro first produces a set of approximate schedules according to the four input files[6]. HASTUS-Micro then creates a set of initial schedules, which usually contains some extras (trippers), based on the approximate Macro schedule. To eliminate these trippers, HASTUS-Micro provides a function (named the *optimization* function) after the generation of an initial Micro schedule. According to the HASTUS manual [76], this function optimally rematches duties and also eliminates as many trippers as possible while still satisfying the work rules and abiding by the manpower constraints of different duty types defined in the parameter file. HASTUS-Macro, which is designed to evaluate the possible cost impact of changes in work rules or other factors much more quickly than a complete scheduling function (such as Micro[7]), can also be operated independently under this batch mode to estimate the total crew cost.

The assignment files, parameter files, selection files, cutting files, and the Macro files which are used as the base for the evaluations presented in the following sections are shown in *Appendix C*. The two output assignment files for Cabot Garage and Albany Garage shown in *Appendixes C1-1* and *C6-1* respectively are the final reports for the manual schedules for fall 1994. The two parameter files (*Appendixes* C2 and *C7*) for both Cabot Garage and Albany Garage were originally used in the corresponding manual interactive crew scheduling processes in fall 1994. These two parameter files are slightly different from the parameter files used in the following evaluations. For example, there is a one-piece part-time duty type defined in the parameter file for Albany Garage as shown in *Appendix C7*. Because trippers are not allowed, this duty type should be deleted. For the comparison between this parameter file which was used in the manual scheduling process and the parameter files used in the following evaluation, the maximum number of runs for

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6 The assignment file, the parameter file, the cutting file, and the macro file. The selection file will be used only in Micro, not Macro.

7 For example, a complete micro schedule for Cabot Garage will take 55 CPU minutes or more on VAX 4000_300 , but it only takes around 5 to 10 CPU minutes to run a macro file for the same garage.

this one-piece part-time duty type is set as 0 instead of eliminating this duty type in the following parameter files. Other differences are summarized below.

4.2.1. The Assignment File

An assignment file is both an input file and an output file. At the beginning of any crew scheduling process (interactive or automated), an assignment file which includes (or corresponds to) the information of relief-point opportunities and vehicle blocks must first be created. This initial assignment file is created based on two files: one is the relief file which contains the information of relief opportunities along the routes served by the specified garage. The other is the vehicle schedule file which includes the vehicle blocks produced by the previous vehicle scheduling process. The relief file is built or modified before the vehicle scheduling process. With the relief file and other necessary information such as the headway sheet and the travel time matrix, HASTUS can create a vehicle schedule as well as a crew schedule.

HASTUS can usually create acceptable vehicle schedules for the MBTA. Blocks created in the vehicle scheduling process include long blocks (e.g. from 7:00 a.m. to 9:00 p.m.) which contain a pull-out at the beginning of the block and a pull-in at the end of the block. Other pull-ins, pull-outs or swings[8] will be added later when the blocks are cut during the crew scheduling process (either manual or automated). The manual or automated crew scheduling processes are performed based on the vehicle blocks and the information on relief opportunities included in this initial assignment file. The initial assignment files created for Cabot and Albany for the manual schedules for fall 1994 are shown in *Appendixes C1* and *C6*. For example, there are 274 long vehicle blocks for the Cabot vehicle schedule for fall 1994. When the initial (input) Cabot assignment file is created, these long blocks are all viewed as extras. All values regarding regular runs are

[8] HASTUS can also create *taxi* trips in the vehicle schedule. In the Cabot and Albany cases, there are no *taxis*.

shown as 0 in that initial assignment file, as are the values in the initial Albany assignment file in *Appendix C6*. In *Appendix C6*, there are 155 extras in this initial assignment file which implies that 155 vehicle blocks were generated in the corresponding vehicle schedule for Albany Garage for fall 1994.

An assignment file is also the output file for the final crew schedule (see *Appendixes C1-1 & C6-1*). It includes information on the number of duties, the average platform time, the number of duties of each type (e.g. straight full-time duties, split full-time duties, part-time duties, and extras), total cost, average hourly rate, etc.[9] There are several important characteristics for a final (output) assignment file. First, some costs (presented as time) are internal (or imaginary), such as *other penalties* for *regular runs* and *overtime* for *extras* (see *Appendix C1*), rather than actual costs (e.g. *platform time*, *paid meal break*, etc.). The actual costs will be reflected in the total reported cost, but the internal costs are just used as internal penalties during the crew scheduling process to discourage the generation of certain duties. For example, HASTUS can discourage the generation of make-up time, swing, or other unproductive paid times in any duty. *Other penalties* for *regular runs* reflect the imaginary cost when these events are scheduled, and *overtime* for *extras* reflect the imaginary cost when any extra is created[10]. The total reported cost does not include these internal costs.

Second, the cost of *signon/off* presented in an assignment file includes not only total swing allowances but also total pull-in and pull-out times. For example, there is a total of 188h06 reported as signon/signoff time for 238 runs in the Cabot Garage manual schedule (see *Appendix C1-1*), i.e. 47 minutes for each run. However, the sign-on allowance for each run at the MBTA is only 10 minutes. After the deduction of this

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[9] Detailed operator assignments (including the specific pieces of work for every run, the associated platform time, duty length, paid premiums, etc.) are also available.

[10] In a parameter file, this cost can be defined in the *extra-rate* and *extra-penalty* parameters. As shown in *Appendix C2-1*, these two parameters were set as 1.5 and 10 respectively for Cabot Garage.

allowance, there are still 37 minutes which represents typical pull-out and pull-in times for a duty at Cabot Garage.

Third, the number of trippers (extras), and the associated platform times are listed separately from other duties, i.e. if there is a tripper in the final report, the number of total runs, and the average platform time shown for all duties do not include trippers[11]. Since an initial assignment file considers all blocks as extras, all values (such as in *Appendix C1*) are shown as zero except for the number of extras, the average platform time for extras, the total platform times for extras, the total overtime penalties (internal costs) of extras, the total reported cost, and the average hourly rate.

Fourth, the total cost shown in an assignment file is only an indicator of the cost rather than the real wage cost. This results from the definition of the wage rate in every parameter file. As shown in *Appendix B* the MBTA union contract specifies wage rates for both full-time and part time operators as a function of seniority, so a senior part-time operator may be paid at the maximum full-time wage rate. However since HASTUS allows only one wage rate for each type of operator, the listed total costs cannot reflect the true wage costs. Thus we will use the total pay hours (the sum of actual time-costs from *platform time* for *regular runs* to *guarantee piece* for *extras* as in *Appendix C1*) instead of the reported total cost in the following evaluations. As will be shown later (see *Table 4-6*, for example), the total pay hours is the sum of 8 individual time-costs. The two internal costs (*other penalties for regular runs* and *overtime for extras*) listed in any final assignment file are not included in the total pay hours. Theoretically, the platform time of extras should not be directly included in the total pay hours, because this value will not equal the actual cost when these extras are actually combined into other duties. In that case, more overtime or spread premiums may occur. Since extras may exist in final automated crew schedules and it seems impossible to find the actual cost for these extras,

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[11] However, the reported cost listed in an assignment file does include the costs of extras.

the reported platform time for extras is still used to represent the potential cost of these small pieces of work.

Fifth, the average platform times shown in an assignment file are revenue (productive) platform times. They do not include either non-revenue pull-out or pull-in times which are included in the reported *signon/signoff* cost as mentioned above.

1. The Assignment File for Cabot Garage (*Appendixes C1, C1-1*): The assignment file shown in *Appendix C1* is the initial assignment file which includes the actual vehicle blocks for Cabot Garage in fall 1994. The actual manual schedule for Cabot Garage in fall 1994 was created based on this initial assignment file. This initial assignment file will also be used as a base initial assignment file for the following evaluations for Cabot Garage.

The assignment file shown in *Appendix C1-1* is the actual manual schedule for Cabot Garage in fall 1994. It will be used as the base crew schedule in the evaluation for the Cabot Garage cases. Apart from the union contract, the parameter files and Macro files used in the evaluation will be constructed by simulating the duties generated in this assignment file. For example, a general split full-time duty type, which can produce similar split full-time duties as those in this actual manual schedule[12], will be built in the following parameter and Macro files. In the actual manual schedule as shown in *Appendix C1-1*, there are three major types of duties, straight full-time duties; split full-time duties, and part-time duties.

The straight full-time duties can be classified into two types: straight duties which start before 5:00 a.m. and others which start after 5:00 a.m. Full-time duties which start before 5:00 a.m. must be straight duties according to the contract. There are 15 full-time duties which start before 5:00 a.m. in the Cabot Garage schedule. Other straight duties which start after 5:00 a.m. are selected by the schedulers. According to the union contract,

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[12] In terms of the number of pieces of work, the platform times, meal-break lengths, etc.

any break in a straight full-time duty must be paid. Each two-piece straight duty has one paid break, while each three-piece duty has two paid breaks[13]. In contrast, not all breaks in split full-time duties and part-time duties are paid.

These 15 duties have to be kept in any schedule as straight full-time duties with a guaranteed paid meal break of at least 20 minutes according to the union contract. However, HASTUS does not provide any function to ensure that any pieces of work starting before 5:00 a.m. will be assigned as a straight full-time duty with a paid meal-break. Since any break within a straight full-time duty is paid, straight full-time duties are usually more expensive than other duty types. Even though there was such a straight full-time duty type built in the Cabot parameter file (*Appendix C2*: the *fto1* duty type) to force any duty type which starts before 5:00 a.m. to be a straight full-time duty, sometimes HASTUS will avoid forming straight full-time duties by assigning these pieces as extras to minimize the cost.

For example, the base optimized final schedule for Cabot Garage in *Table 4-4* is the optimized automated (Micro) schedule based on the initial assignment file in *Appendix C1*. No run was fixed before the automated crew scheduling process for the base schedule and a straight full-time duty type, which is almost identical to the *fto1* duty type in *Appendix C2,* was defined in the parameter file for this base schedule. However, 17 extras including 15 which start before 5:00 a.m. were created in the base schedule by HASTUS, i.e. HASTUS did not absolutely follow the straight full-time duty type in the parameter file to assign these 15 pieces of work as straight full-time duties. In the contrast, the test schedule is the final optimized schedule which had 15 straight runs fixed in advance. The number of extras has been reduced from 17 to 2. Certain duties which were originally

[13] In the MBTA, these two breaks are classified into two types: one is the paid meal break, and the other is the paid join-up time. Therefore, it can be said that a 3-piece straight duty has one paid meal break and one paid join-up time. The join-up time is similar to the travel time between two pieces of work.

assigned as straight full-time duties in the base schedule were assigned as split full-time duties and part-time duties in the test schedule.

Table 4-4: Micro Schedules with and without Fixed Runs

1. Cabot Garage				2. Albany Garage			
	manual	Base	Test 1		manual	Base	Test 1
Fixed runs		0	15	Fixed runs		0	5
Optimization		After	After	Optimization		After	After
Period length		34	34	Period length		34	34
# of fto-str	28	24	17	# of fto-str	13	9	12
2-piece	26	23	16	2-piece	13	9	10
3-piece	2	1	1	3-piece			2
Platform time	6h34	6h14	6h31	Platform time	6h05	6h07	5h59
# of fto-spl	154	150	172	# of fto-spl	72	72	68
2-piece	108	117	121	2-piece	57	60	56
3-piece	42	33	51	3-piece	14	12	12
4-piece	4			4-piece	1		
Platform time	7h04	6h58	6h53	Platform time	6h30	6h32	6h33
# of pto	56	59	56	# of pto	45	47	48
1-piece	2	7	16	1-piece			
2-piece	54	50	40	2-piece	44	47	48
3-piece		2		3-piece	1		
Platform time	4h56	4h44	4h22	Platform time	4h21	4h17	4h20
Total Runs	238	233	245	Total Runs	130	128	128
Platform time	6h30.58	6h20.11	6h17.33	Platform time	5h43.07	5h41.14	5h40.30
# of extras	0	17	2	# of extras	0	4	4
Platofrm time	0h00	4h49	3h46	Platofrm time	0h00	4h24	4h50
Re. T. platform	1550h53	1476h25	1541h42	Re. T. platform	743h27	727h59	726h26
Sign-on/pull	186h06	189h06	201h26	Sign-on	160h06	158h48	158h19
Join-up	11h30	13h23	20h41	Join-up	4h48	6h00	6h45
Paid meal	14h05	24h16	18h07	Paid meal	7h25	7h05	6h42
Guaranteed run	3h12	0h00	0h05	Guaranteed run	11h35	0h00	0h40
Overtime	32h55	24h58	27h24	Overtime	8h38	12h55	9h13
Spread rate 1	9h44	14h57	29h11	Spread rate 1	1h48	11h49	8h43
Spread rate 2	0h00	9h07	28h00	Spread rate 2	0h00	10h29	8h47
Extra platform	0h00	82h03	7h33	Extra platform	0h00	17h36	19h23
To. pay hour	1808.42	1834.25	1874.15	To. pay hour	937.38	952.68	944.97

Optimizatiom: Before or after the use of the optimization function which is used after the generation of initial micro schedules.
Period length: The specified period length
# of fto-str: Number of straight full-time duties
# of fto-spl: Number of split full-time duties
# of pto: Number of part-time duties
Platofrm time: Average revenue platform time. It does not include unproductive pull-in and pull-out times.
Re. T. platform: Total platform times of regular runs
Sign-on/pull: Total sign-on times and total pull-in vs. pull-out times of regular runs
Join-up: Total paid join-up times of regular runs
Paid meal: Total paid meal break of regular runs
Guaranteed run: Total make-up times of regular runs
Overtime: Total weighted overtime penalties of regular runs
Spread rate 1 (> 10 hrs): Spread premiums for regular runs whose duty lengths exceed 10 hrs.
Spread rate 2 (> 11 hrs): Spread premiums for regular runs whose duty lengths exceed 11 hrs.
Extra platform: Total platform times of trippers
To. pay hour: Total pay hour

Therefore, in order to ensure that these 15 duties will appear as straight full-time duties, they must be fixed before any automatic crew scheduling process (Micro or Macro) for Cabot Garage. By fixing these 15 duties, HASTUS will not change them during any automatic crew scheduling process.

Split full-time duties are of 3 types: morning-split duties which cover the morning peak but start after 5:00 a.m., evening-split duties which start in the afternoon and cover the evening peak, and the multiple-piece (3-piece or 4-piece) split duties which can start any time after 5:00 a.m. A three-piece duty has one paid join-up time while a 4-piece duty has two paid join-up lengths. In general, any join-up length in any duty will be kept short. Part-time operators typically work both peaks and thus have two-piece duties. However, because trippers are not allowed at the MBTA, there are two short pieces of work which are assigned as one-piece part-time duties in the manual schedule.

2. The Assignment File for Albany Garage(*Appendixes C6, C6-1*): The assignment file shown in *Appendix C6* is the initial assignment file which includes the actual vehicle blocks for Albany Garage in fall 1994. The actual manual schedule for Albany Garage in fall 1994 was created based on this initial assignment file. This initial assignment file will also be used as a base initial assignment file for the following evaluations for Albany Garage. The assignment file shown in *Appendix C6-1* is also the actual manual schedule for Albany Garage in fall 1994. In this assignment file, there are 5 straight full-time duties that start before 5:00 a.m. in the Albany manual schedule. As shown in *Table 4-4*, initially these 5 pieces of work which start before 5:00 a.m. were not fixed in advance in the base schedule. As in Cabot, HASTUS cannot guarantee to assign this kind of work as straight full-time duties as defined in the parameter file, so 3 such pieces of work were assigned as trippers by HASTUS. After fixing 5 straight duties in the test schedule, the 4 trippers created in the test schedule no longer included any piece of work starting before 5:00 a.m.. As a result, these 5 duties must be fixed before any automated crew scheduling process for Albany Garage. Unlike Cabot, fixing these 5 straight full-time runs did not result in an increase in total pay hours.

Aside from these 5 straight duties, 8 more straight duties which start after 5:00 a.m. were created manually. Neither three-piece straight full-time duties nor one-piece part-time duties were generated in the manual schedule.

4.2.2 The Parameter File

The work rules and the desired duty types are defined in the parameter file. These are usually called "hard rules", because they follow the union contract and cannot be changed arbitrarily or unilaterally. However, even though parameters in the parameter file are viewed as "hard rules", HASTUS-Micro does not guarantee not to violate all of them during the scheduling process. For example, Micro automated crew schedules sometimes may violate certain parameter settings, such as a constraint on the number of total runs, constraints on the maximum number of runs of each duty type, etc. (see *Appendixes C2, C7*). The parameter file can be used in both the interactive (manual) and the batch (automatic) crew scheduling functions.

The parameter file allows only two wage rates for two types of duties: one for full-time duties and the other for part-time duties. As mentioned above, the wage rates for both full-time and part time operators are usually a function of seniority. In such a case, the choice of the wage rates for both full-time and part-time operators will not only affect the final reported costs, but may also affect the resulting crew schedule. For example, raising the nominal wage rate for part-time duties will tend to reduce the number of these duties included in the final solution.

Appendixes C2 and *C7* are only part of the complete parameter files (see *Appendixes C2-1* and *C7-1*) for Cabot and Albany, but they contain the most important parameters in the parameter files and are the only parameters which are changed in the following evaluations.

1. The Parameter File for Cabot Garage (*Appendixes C2, C2-1*): As shown in *Appendix C2*, three full-time duty types and one part-time duty type are included in the parameter file. The first duty type represents straight full-time duties. In addition to the 15 fixed straight duties, there are 13 more straight duties in the manual schedule. Thus in the parameter file, no restrictions are placed on the starting time of straight duties i.e. if HASTUS decides to form a straight duty (2-piece or 3-piece) apart from those fixed straight duties, it can start anytime. Because this is a straight duty (any break is paid), the maximum spread time is set at 8 hours 5 minutes.

The second full-time duty type represents two-piece split full-time duties. The third full-time duty type represents split full-time duties which contain more than two pieces of work. All part-time duties (1-piece, 2-piece or more) are represented by the fourth duty type. The parameter file also sets up the minimum and maximum platform times for each duty type.

The manpower constraints, such as the total runs, and the maximum number of a specific duty type, in this manual parameter file are slightly different from those used in the following evaluations. In the manual parameter file (*Appendix C2*), the total-run constraint was set at 233 and the maximum number of part-time duties was set at 53. Without knowing if Micro is able to produce a better schedule in terms of the manpower, we adjust these parameters by using the manpower derived in the manual schedule (see *Appendix C1*) as upper limits, i.e. the total run constraint is relaxed to 238 while the maximum number of part-time duties is set at 56[14]. In addition, we also lower the maximum number of straight duties from 18 to 13, because there are just 28 straight full-time duties in the manual schedule[15]. Since these two maximum manpower constraints have been imposed on straight full-time duties and part-time duties, no maximum manpower constraint is added to either type of split full-time duty, i.e. if HASTUS wants to increase the number of duties, split full-time duties would be preferred over the other two duty types.

Other parameters are set according to the union contract terms except for the maximum spread-length parameter. The maximum spread-length constraint for all duties is 13 hours, however, it is restricted to 11 hours for full-time duties as a soft rule for the

[14] Since more part-time duties are not desired in the MBTA, the current assigned part-time duties in the manual schedule are set as the upper limit in the parameter files in the following evaluation for both garages.

[15] We already have fixed 15 straight duties. These duties will not be included while considering the manpower constraint for this specific duty type. Therefore, the minimum and maximum number of full-time straight duties are set as 0 and 13 respectively, not 15 and 28.

manual scheduling process in the MBTA to prevent long spread lengths (with greater spread premiums). This soft rule is employed in the following evaluations for both garages.

The one-minute relief allowance is a special parameter in this parameter file. It is not a paid allowance as is the 20-minute swing allowance parameter. Rather it is used to require HASTUS to assign an extra minute to every switch-on piece of work. For example, an operator will be assigned to take over a piece of work, which starts at 9:30 a.m., at 9:29 a.m..

2. The Parameter File for Albany Garage (*Appendixes C7, C7-1*): The duty types established in the parameter file for Albany Garage are very similar to those for Cabot Garage. The differences are that straight full-time duties are divided into two types in the Albany parameter file: one is the 2-piece straight duty that starts before 5:00 a.m.; the other is the 2-piece or 3-piece (which has a paid join-up period) that starts after 5:00 a.m.. As mentioned above, these two parameter files (*Appendixes C2* and *C7*) are the files used in the manual crew scheduling process and were built before the evaluation in this thesis. Early tests in the previous section showed that the pieces of work which start before 5:00 a.m. at both garages could not all be combined into straight full-time duties by HASTUS even if the straight full-time duty types (in two parameter files for two garages) were built. Some of these pieces of work would be left as trippers. Therefore, these pieces of work have to be fixed as straight full-time duties for both garages before any automated crew scheduling process. Even though the straight full-time duty type which starts before 5:00 a.m. is useless after fixing these pieces of work, this duty type is not excluded from the parameter files in the following evaluation for as the comparison between these files and the manual parameter file, as is the one-piece part-time duty type.

Part-time duties are divided into two categories. The first part-time duty type is the one-piece duty while the second duty type is for two-piece and three-piece part-time duties. The maximum number of one-piece part-time duties was originally set as 9 (See

Appendix C7). As mentioned above, the maximum number of runs for this one-piece part-time duty type is set at 0 in the parameter files in the following evaluations. Since more part-time duties are not desired in the MBTA, the maximum number of the second part-time duty type is set as 45 which is the same as the number of part-time duties assigned in the manual schedule, i.e. the number of part-time duties in the following crew schedules should not exceed the assigned part-time duties in the manual schedule.

Other manpower constraints of the Albany Garage parameter file applied in the following evaluation are also somewhat different from those in the manual parameter file (*Appendix C7*). The part-time and full-time duties required in the manual schedule are used as upper limits in the parameter file applied in the following evaluation. The total-run constraint is increase from 119 to 130. The maximum numbers of runs for two straight full-time duty types are set as 8 (13 required straight duties minus 5 fixed straight duties). For the same reason discussed in the Cabot Garage parameter file, no upper limit was added to the maximum number of runs for both split full-time duty types.

4.2.3. The Selection File

In contrast to a parameter file, a selection file includes "soft rules". According to the HASTUS manual [76], a selection file can give more control over a run cut without modifying the hard rules in a parameter file. A scheduler can strengthen the restrictions or the expectations for his ideal final schedule by establishing some extra criteria in the file[16]. For example, a large penalty (e.g. 9999) can be added to prevent any extra ending between 7:30 p.m. and 11:30 p.m. (similar to the 11th constraint in *Appendix C3*). This cost is applied only when the optimization procedure is executed [75]. The final reported cost will not include this kind of cost, since it is intended only to guide the solution.

[16] These criteria, of course, should not violate the hard rules.

In fact the selection file, the cutting file, and the Macro file all have a similar "soft" nature. HASTUS will not guarantee to follow these inputs absolutely when producing the ideal schedule defined by these files (or schedulers). Also because of their soft nature, the selection file or cutting file may have little influence on the final schedule.

1. The Selection File for Cabot Garage (*Appendix C3*): Several types of penalties are included in this selection file. First, a penalty is added to prevent a duty which ends within a specific period having a certain spread. For example, a penalty of 9999 (100) is included in the first (second) constraint to discourage any split full-time duty which ends between 9:00 p.m. and 2:00 a.m. next morning (between 6:00 p.m. and 9:59 p.m.) from having a spread over (less than) 10 hours[17] (see *Appendixes C3 and C8*). The first constraint ensures that no operator ending his duty very late has a long spread time.

Second, penalties are added to encourage creating duties with certain desired platform times. For example, the fifth constraint penalizes any split full-time duty not having a platform time from 7 hours 46 minutes to 8 hours 5 minutes. Any duty which does not have this platform time incurs a penalty in proportion to the stated penalty ($300 in this case) and the gap between its platform time and this ideal length. This kind of constraint is used to help produce more productive duties (higher platform times) in an automated crew schedule solution.

Third, a penalty is added to a specific route (e.g. Route 9700) to prevent any tripper[18] being produced along this route, such as the sixth constraint. A similar penalty could also be added to prevent any tripper ending in a specific period, such as the eleventh constraint. Fourth, a negative penalty is also added to encourage generating a full-time three-piece split duty, such as the seventh constraint. This constraint is used to discourage

[17] Different penalties, such as 9999 or 100, are used to distinguish the preferences between specified restrictions. For example, the penalty of 9999 strongly suggests HASTUS not violate the specified restriction. However, unlike the union contract, these "soft" constraints (even with the penalty of 9999) can still be over-ridden by HASTUS.

[18] The parameter of run-number-pieces is set at 0 by HASTUS to represent trippers.

the generation of trippers by combining small pieces of work into other duty types. In contrast, a penalty is added to prevent the generation of a straight full-time duty (the tenth constraint) because of its higher cost due to the paid meal break. Fifth, the last constraint discourages any split full-time duty ending between 8:00 p.m. and 2:00 a.m. from having a meal break in the evening peak hours.

2. The Selection File for Albany Garage (*Appendix C8*): The selection file for Albany Garage is the same as that for Cabot Garage except that no platform-time constraint was added in the Albany Garage selection file. Unlike Cabot Garage, previous tests of automated crew schedules for Albany Garage were usually able to produce duties with satisfactory average platform times for all duty types.

4.2.4. The Cutting File

A cutting file is used to define certain forbidden or desirable relief opportunities for a specified bus garage (route, or transit line), for the specified period. For example, a penalty of 9999 can be imposed in the cutting file to discourage reliefs at certain places (see the 1st constraint in *Appendix C4*). The difference between a selection file and a cutting file is that a cutting file penalizes certain pieces as the blocks are cut, while a selection file penalizes the pieces of work when they are built into duties [75]. As with the selection file, this kind of penalty will not be reflected in the final reported cost.

1. The Cutting File for Cabot Garage (*Appendix C4*): Three major types of constraints are defined in this file. First, constraints are set to prohibit any cuts at certain places (maybe in a specified period). For example, the MBTA does not want any vehicle blocks cut at Central Square (the 3rd constraint) or at Harvard Square (the 7th constraint).

Second, swing duties are not desired in certain periods. For example, the 4th constraint discourages any swing in or after the afternoon peak period. Any swing should be assigned before the afternoon peak period to minimize the potential impact on operations. There is a risk that a scheduled trip after a swing will be delayed during the peak hours, because of possible vehicle congestion delays.

Third, the 10th constraint was set to ensure that no cut occurring during the evening peak leaves a piece of less than 2 hours in length. It is better to cut a block either before or after the evening peak. If a cut occurs during the peak hour, the vehicle and the manpower requirements will increase because a new vehicle (operator) is required to pull out of the garage to keep the schedule when the off-duty vehicle (operator) is pulling back to the garage[19]. Besides, if the cut occurs before the evening peak, an early split full-time duty (or even a 3-piece duty) could be generated. If a cut occurs after the evening peak, an evening split full-time duty (or 3-piece duty) could be produced. A cut within the evening peak hours might not only affect the operation, but might also makes the scheduling task more difficult because of the overtime and the spread constraints.

The last constraint (11th) is a very special constraint. String 22 is included in one of the 15 fixed straight full-time duties. The cut in this period for String 22 was originally a swing at Cabot Garage, but HASTUS changed it to a combination pull-in and pull-out. This change would result in a higher cost because of the extra pull-in and pull-out times. So, the constraint was introduced to ensure that this swing will not be changed during the automated crew scheduling process.

2. The Cutting File for Albany Garage (*Appendix C9*): As mentioned above, street reliefs are not allowed in any Albany Garage crew schedule. As a result, more places were restricted by the constraint that prohibits cutting at any time.

[19] The start point of a trip may not be close to the garage. There has to be some travel time between the garage and this start point, so there has to be some overlap between pull-in and pull-out times to keep the schedule. Therefore, it is usually impossible for a single vehicle (operator) to cover both pull-in and pull-out.

4.2.5 The Macro File

A Macro file is built to approximate the work rules and is used to produce approximate crew duties as a basis for the generation of real runs in Micro. All the time definitions in a Macro file have to be consistent with (i.e. multiples of) the specified period length. For example, the 6th constraint (the guaranteed-piece constraint: the minimum length of a piece of work) in *Appendix C5* is defined as 2h04 for the period length of 31 minutes, while it may be set as 2h08[20] for the period length of 32 minutes. Consequently the choice of an appropriate period length and the creation of a corresponding Macro file may be important. Different period lengths employed in the Macro files may affect the distribution of vehicle blocks and the cutting and matching in HASTUS and may result in different final crew schedules. For example, a block which starts at 5:11 a.m. will be assigned to the thirteenth period[21] in a Macro file with a 24-minute period length , while it will be assigned to the eleventh period in a Macro file with a 31-minute period length. Every block assigned to a period implies that one operator (duty) is required in this period. Since Macro focuses on the manpower requirements, the cutting of blocks, and the matching of pieces of work between periods instead of by actual starting or ending time[22], different distributions of blocks may result in different assignments of manpower, different combinations of pieces of work, and hence result in different final schedules.

According to the discussion above, a short period length may be better for any Macro file, because the shorter it is, the better it can approximate the actual starting and ending times of the blocks (the pieces of work or the resulting duties) and also other criteria, such as pay hour guarantee, spread constraint, etc. However, a short period length

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[20] 2h04=124 minutes=31 minutes*3; 2h08=128 minutes=32 minutes*4.

[21] 4:24 a.m. to 4:48 a.m. is the twelfth period, and 4:48 a.m. to 5:12 a.m. is the thirteenth period. (4 hours 48 minutes ÷ 24 minutes = 12; 5 hours 12 minutes ÷ 31 minutes = 13). 5:11 a.m. lies between 4:48 a.m. and 5:12 a.m..

[22] For example, HASTUS will match two pieces of work one of which ends at Period 13 and the other which starts at Period 15, no matter the actual ending for the first piece of work and the starting time for the second piece of work as long as they fall in these periods -- these two pieces of work may not be connected when the actual ending and starting times are considered.

sometimes will fail to create a feasible Macro file because of limitations in the problem size solvable with HASTUS-Macro. Macro can deal with at most 2900 variables[23]. If the period length becomes shorter, the number of variables increases because the possible cutting and/or matching opportunities increase. For example, if there are three pieces of work which start at 9:10, 9:30, and 9:50 a.m. respectively, they will be allocated to three different periods (9:00-9:20, 9:20-9:40, 9:40-10:00) in a Macro file with a 20-minute period length. However, these 3 pieces of work will be allocated to only one period (9:00-10:00 a.m.) in a Macro file with a 60-minute period length. The increase of the number of periods will increase the number of variables and when the number of variables exceeds the limit, the Macro file will become infeasible.

1. The Macro File for Cabot Garage (*Appendix C5*): A period length is selected by checking if it can approximate most of the actual required time definitions[24]. If a period length can approximate most times well, it may help Macro create a schedule which is close to the actual schedule. For example, the period lengths of 31 minutes and 34 minutes are able to approximate most of the work rules well, including the minimum paid length for full-time operators (6h50), the maximum paid length for full-time operators without paying the overtime premium (7h50), and the maximum spread length for part-time operators (13h00)[25]. The use of these period lengths may help Macro cut the blocks and match pieces of work close to the actual schedule. Therefore, these two period lengths are used for Cabot (31 minutes) and Albany (34 minutes) respectively.

The Macro constraints (or parameters) can be roughly divided into two groups: the global constraints which are applied to all duty types (the 2nd to 14th constraints) and

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[23] According to the Macro manual [77], the maximum number of variables should be 4000. However, the Macro computer software installed at the MBTA can deal with at most 2900 variables.

[24] A detailed assessment of different period lengths will be presented in *section 4.3*.

[25] 31 minutes * 12=6h12, 31 minutes * 13=6h43, 31 minutes * 15=7h45, 31 minutes * 25=12h55; 34 minutes * 11=6h14, 34 minutes * 12=6h48, 34 minutes * 14=7h56, 34 minutes * 23=13h02.

the local constraints which are applied to a specified duty type (the 19th to 95th constraints for different duty types).

The Macro file is established by simulating the duty types in the manual schedule and the union contract of the MBTA. In the Cabot Garage Macro file, two more duty types are added compared with the parameter file. First, the second duty type (split full-time duties) in the parameter file is divided into two: the two-piece early split duty and the two-piece evening split duty type. The range-start constraints (the 31st and 63rd constraints) and the max-spread constraints (the 37th and 69th constraints) are different between these two duty types with the late split duty having a smaller maximum spread, because the evening split duties are not expected to have long spreads.

Second, a one-piece duty type (tripper) is created to discourage the generation of trippers and to keep the length of trippers in a certain range by setting constraints. For example, the tripper-factor constraint (the 93rd constraint in *Appendix C5*) is used to produce trippers whose lengths are less than 3 hours 37 minutes[26]. With this kind of small tripper, it may be possible for Micro to combine them into other duty types. Besides, it is much easier to massage this kind of tripper into other duties in the manual scheduling process.

As mentioned above, Macro has a limitation in the total number of variables it can handle. Unfortunately, the three-piece duty defined in this Macro file usually will generate a large number of variables. For example, the range-start constraint (the 47th constraint) of the three-piece duty type was originally set from 10h20 to 14h28, while the meal break-length constraint (the 51st constraint) of the three-piece duty type was set from 1h33 to 5h41 and the piece-length constraint (the 54th constraint) was set from 2h04 to 5h10. When this Macro file was executed in HASTUS-Macro, the number of three-piece duty

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[26] The penalty of 15 used in this parameter means that for any tripper with length over this specified constraint, a cost will be imposed which equals the product of the regular pay rate and this factor (15). The penalties used in a macro file will not be reflected in the final reported cost as for those in a selection file or a cutting file.

variables alone exceeded 2900. It was thus infeasible to produce a Macro schedule, not to mention a Micro schedule. This Macro file became feasible only after the range-start constraint of the three-piece duty type was lowered to 10h20 to 12h55 and the range of the mealbreak-length constraint of the three-piece duty type was lowered to 1h33 to 2h35. The piece-length constraint was also lowered to 2h04 to 4h08.

2. The Macro file for Albany Garage (*Appendix C10*): The Albany Garage Macro file still simulated those duties generated in the manual schedule as its corresponding parameter file. For example, a split full-time duty type was built according the features[27] of those split full-time duties produced in the manual schedule. The structure of the Albany Garage file is very similar to the Cabot Garage Macro file (see *Appendix C10* and *C5*). The straight full-time duty type, the split full-time duty type, and the part-time duty type were built in the Albany Garage Macro file.

Because almost all the duties will end before 9:00 p.m., it is not necessary to build an independent evening split full-time duty type as in the Cabot Garage Macro file. The 2-piece early split full-time duty, the 3-piece split full-time duty, and the 2-piece late split full-time duty in the Cabot Macro file are combined into one duty type here. Instead of defining an independent tripper duty type as in the Cabot Garage Macro file, similar constraints (i.e. the 16th to 18th constraints) were included as global constraints, i.e. the tripper constraints were applied to all duty types.

[27] The starting times, the number of pieces of a split full-time duty, the duty length, etc.

4.3 Evaluation of HASTUS in the MBTA Context

As discussed in chapter 3, HASTUS has been shown to be very helpful in improving the efficiency of transit scheduling at many transit agencies. Since the automatic crew scheduling function has not been fully used at the MBTA, it is of interest to see if HASTUS can also produce acceptable schedules and achieve additional benefits in the MBTA context. The evaluation in the thesis can be briefly classified into two parts. The first part of the evaluation in *section 4.3.2* explores the Macro and Micro functions for both Cabot and Albany in the MBTA context. The difference between an initial Micro schedule and its corresponding optimized Micro schedule is first discussed in *section 4.3.2.1*. Two important parameters (the part-time operator wage rate and the maximum number of part-time operators) which should be able to influence the number of part-time duties as desired by the MBTA are then examined in *sections 4.3.2.2* and *section 4.3.2.3* respectively. As mentioned previously, different period lengths may affect final Macro and Micro schedules. This kind of impact is examined in *section 4.3.2.4*. The relationship between different Macro schedules and their corresponding Micro schedules is also examined in this section. The consistency between these two kinds of crew schedules is carefully examined.

The second part of the evaluation in *section 4.3.3* performs sensitivity analysis based on the Macro and Micro schedules derived in the first part. The impact of different input files on the final Micro schedule is first examined in *section 4.3.3.1*. The effect of several important parameters used in the Macro file are then explored in *section 4.3.3.2*. *Section 4.3.3.3* relaxes certain soft rules to examine the impact on the Cabot Garage case.

Several different work rules are imposed on the Albany Garage case in *section*

4.3.4 to examine the relevant impacts and the correlation between the resulting Macro and Micro schedules.

4.3.1 The Manual Schedules

One main objective of the MBTA in the crew scheduling process is to satisfy the manpower constraints, for both full-time and part-time operators. It is worth comparing the cost to the MBTA of part-time and full-time operators before looking at the scheduling implications. Currently an MBTA part-time operator receives the same health insurance package (costing the Authority around $800 per month) as a full-time operator, and it requires four part-time operators (at no more than 30 hours per week each) to cover the work of three full-time operators (at about 40 hours per week). However the savings resulting from the spread premium[28] which would be paid to full-time operators can still justify the cost of employing an extra part-time operator. For example, every 4 part-time operators will cost an extra $800 health insurance per month compared with 3 full-time operators for the same workload. Prior to the employment of part-time operators, spreads for full-time duties were often as high as 11 hours to 13 hours. If the marginal spread for full-time duties is 11.5 hours, 3 full-time operators may cost the Authority $1100 in spread premiums per month[29]. In such a case, the employment of part-time operators will still be more economical despite the $800 additional health insurance cost.

There are additional considerations in choosing the right combination of part-time and full-time operators. First, a new operator undergoes training for 3 to 4 weeks. According to the Permanent Movement Report for MBTA Subway Operations, the attrition for part-time operators was 16%[30] in the period from November 1st, 1993 to

[28] There is no spread premium for part-time operators (See the MBTA union contract in *Appendix B*).
[29] ((0.5 (spread premium for the spread between 10 hours and 11 hours) * 1hr) + (1 (spread premium for the spread over 11 hours) * 0.5 hr)) * $18.46 (full-time wage rate/per hour) * 3 (full-time operators) * 20 (weekdays per month) = $1107.6
[30] During this period, there were 24 terminations among 148 part-time subway operators,

December 30th, 1994, compared with 6% for full-time operators. Since the attrition rate for part-time operators is higher than full-time operators, greater reliance on part time operators will increase some types of cost[31] as well as the difficulty of management. Second, in the future, it is possible that part-time operators may be paid for swing allowance, and spread premiums[32] as are full-time operators.

Table 4-5: The Manual Schedules (Fall 1994)

	Full-time Straight duties	Full-time Split duties	Part-time duties	Total Runs	Total Cost	Total Pay Hours
Cabot	2-piece: 26 3-piece: 2	2-piece: 108 3-piece: 42 4-piece: 4	1-piece: 2 2-piece: 54	238	32488.43	1808.42
Albany	2-piece: 13	2-piece: 57 3-piece: 14 4-piece: 1	2-piece: 44 3-piece: 1	130	16389.33	937.38

Tables 4-5 shows the manual schedules for Cabot Garage and Albany Garage in fall 1994 respectively. There were 56 part-time operators and 182 full-time operators for Cabot Garage in fall 1994, while 45 part-time operators and 85 full-time operators were required for Albany Garage. Total required runs in Cabot is almost twice that in Albany and more 3-piece (or 4-piece) full-time duties were required at Cabot (42, or 18% of total runs) than at Albany (14, or 11% of total runs). In order not to violate the union contract (such as the tripper prohibition, and the duty length constraint, etc.), the MBTA sometimes has to pay the join-up times and spread premiums associated with 3-piece or 4-piece duties in the manual schedules.

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compared with 92 terminations among 1462 full-time subway operators. The terminations resulted from retirements, discharges, and temporary layoffs. Although the statistics are from the subway system, it also represents the general results in the MBTA.

[31] This cost includes the dollar costs such as uniform fees, training costs, and other non-monetary costs such as the cost resulting from management problems, etc.

[32] These are proposed by the union.

4.3.2 Macro and Micro Schedules

4.3.2.1 Initial Micro Schedules

As mentioned before, Micro creates an initial crew schedule based on a Macro relaxed crew schedule. This initial Micro solution does not necessarily abide by the rules defined for the automated crew scheduling process. For example, trippers are not allowed in the MBTA. However, even though certain parameters in the parameter file as well as the Macro file[33] can be used to limit the generation of trippers through internal costs, HASTUS would still frequently create trippers in an initial schedule. HASTUS also usually creates more part-time duties in an initial solution than the maximum number (usually set as the required manpower in the manual schedules) defined in the parameter file. It tends to produce part-time duties instead of full-time duties to minimize the total cost.

All the test (after) schedules in *Tables 4-6* and *4-7* are the optimized schedules associated with the corresponding base schedules each of which has a different PTO wage rate. Several conclusions are clear from this table. First, the optimization function does indeed eliminate trippers for both garages. For Cabot, the second case whose initial schedule had 80 trippers was left without a single tripper after optimization. In the other two schedules for Cabot only a single tripper remains, and Albany has no trippers. This function also reduced the number of part-time duties to the range of 69-71 for Cabot Garage and from 49 to 45 in the case of Albany Garage. Although a significant number of part-time duties have been eliminated in the Cabot Garage schedules, the optimized schedules for Cabot still have far more part-time duties than the allowed upper limit (56 part-time duties in the manual schedule).

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33 Such as the *extra-penalty* parameter and the *extra-rate* parameter in *Appendix C2-1*, or the *tripper-factor* and other related parameters in *Appendix C10.*

Table 4-6: Micro Automated Crew Schedules for Cabot Garage

	manual	Base 1	(%)	Test 1-1	(%)	Base 2	(%)	Test 2-1	(%)	Base 3	(%)	Test 3-1	(%)
Optimization		Before		After		Before		After		Before		After	
PTO wage rate	13.85	10		10		20		20		30		30	
Period length		31		31		31		31		31		31	
# of flo-str	28	16	-42.9	15	-46.4	32	14.3	17	-39.3	16	-42.9	18	-35.7
2-piece	26	16		15		32		17		16		18	
3-piece	2												
Platform time	6h34	6h34		6h35		6h14		6h29		6h34		6h27	
# of flo-spl	154	105	-31.8	167	8.4	118	-23.4	169	9.7	102	-33.8	164	6.5
2-piece	108	79		140		87		143		75		136	
3-piece	42	26		27		31		26		27		28	
4-piece	4												
Platform time	7h04	7h01		6h44		7h04		6h43		7h01		6h50	
# of pto	56	127	127	71	26.8	42	-25.0	69	23.2	129	130	70	25.0
1-piece	2	57		32				34		57		30	
2-piece	54	69		39		41		35		71		40	
3-piece		1				1				1			
Platform time	4h56	4h45		4h33		4h53		4h26		4h47		4h24	
Total Runs	238	248	4.2	253	6.3	192	-19.3	255	7.1	247	3.8	252	5.9
Platform time	6h30.58	5h50.11		6h06.43		6h27.41		6h05.14		5h49.42		6h08.05	
# of extras	0	36		1		80		0		38		1	
Platform time	0h00	3h20		5h56		4h20		0h00		3h22		5h56	
Re. T. platform	1550h53	1447h28		1546h23		1240h36		1552h15		1439h40		1545h58	
sign-on/pull	186h06	174h13		191h58		155h29		192h05		175h40		193h29	
join-up	11h30	4h04		4h19		7h32		5h12		4h44		4h44	
paid meal	14h05	8h03		8h51		22h48		11h24		8h28		10h56	
Guaranteed run	3h12	15h37		43h58		6h10		47h38		12h58		31h12	
Overtime	32h55	17h13		7h44		25h19		8h47		18h44		17h06	
Spread rate 1	9h44	10h01		5h31		8h02		5h40		10h41		6h15	
Extra platform	0h00	120h28		5h56		347h30		0h00		127h59		5h56	
To. pay hour	1808.42	1797.12	-0.62	1814.67	0.35	1813.43	0.28	1823.02	0.81	1798.90	-0.53	1815.60	0.40

PTO wage rate: The part-time operator wage defined in the parameter file.

Table 4-7: Micro Automated Crew Schedules for Albany Garage

	manual	Base 1	(%)	Test 1-1	(%)	Base 2	(%)	Test 2-1	(%)	Base 3	(%)	Test 3-1	(%)
Optimization		Before		After		Before		After		Before		After	
PTO wage rate	13.85	10		10		20		20		30		30	
Period length		34		34		34		34		34		34	
# of flo-str	13	5	-61.5	7	-46.2	5	-61.5	7	-46.2	5	-61.5	8	-38.5
2-piece	13	5		7		5		7		5		8	
3-piece													
Platform	6h05	6h02		6h04		6h02		6h00		6h02		5h57	
# of flo-spl	72	76	5.6	78	8.3	75	4.2	78	8.3	76	5.6	79	9.7
2-piece	57	76		77		75		77		76		78	
3-piece	14			1				1				1	
4-piece	1												
Platform	6h30	6h32		6h27		6h36		6h30		6h36		6h31	
# of pto	45	49	8.9	45	0.0	49	8.9	45	0.0	49	8.9	43	-4.4
1-piece													
2-piece	44	48		45		48		45		48		43	
3-piece	1	1				1				1			
Platform	4h21	4h26		4h24		4h22		4h20		4h21		4h14	
Total Runs	130	130	0.0	130	0.0	129	-0.8	130	0.0	130	0.0	130	0.0
Platform	5h43.07	5h43.59		5h43.59		5h44.26		5h44.08		5h44.11		5h44.11	
# of extras	0	0		0		2		0		0		0	
Platform	0h00	0h00		0h00		3h18		0h00		0h00		0h00	
Re. T. platform	743h27	745h18		745h18		740h33		745h39		745h45		745h45	
sign-on/pull	160h06	154h28		154h46		152h46		154h40		154h35		154h48	
join-up	4h48	0h28		0h15		0h28		0h15		0h28		0h15	
paid meal	7h25	2h39		3h59		2h39		3h33		2h39		4h23	
Guaranteed run	11h35	10h21		16h16		7h14		14h23		9h18		16h48	
Overtime	8h38	4h01		1h53		6h30		3h53		8h04		7h16	
Spread rate 1	1h48	5h30		4h51		5h08		4h23		6h49		6h09	
Extra platform	0h00	0h00		0h00		6h37		0h00		0h00		0h00	
To. pay hour	937.78	922.75	-1.6	927.3	-1.1	921.92	-1.69	926.77	-1.17	927.63	-1.08	935.4	-0.25

Compared with the initial schedules, the optimized Cabot schedules have much lower average platform times[34] (for split full-time duties, part-time duties, and the total average platform time) and marginally higher total pay hours than the initial schedules. The lower average platform times in the optimized schedules may result from the re-matching of small pieces of work (trippers or original part-time duties) into split full-time duties and part-time duties. This rematch thus increases the number of split full-time duties by 51 to 62 and decreases the number of part-time duties by about 60. The lower average platform times certainly increase the make-up time-costs (shown as *Guaranteed run* in the tables). Compared with the overtime penalties, spread premiums, and required manpower, it seemed that HASTUS prefers paying more make-up time-costs (lower average platform times) than overtime penalties and spread premiums, even though required manpower might increase.

Compared with the Cabot manual schedule, HASTUS is inclined to prevent the paid meal break by producing more split full-time duties instead of straight full-time duties. It is also inclined to discourage overtime and spread premiums by lowering average platform times.

As shown in *Table 4-6*, the average platform time for both split full-time duties, and for part-time duties are 20-30 minutes lower than for the manual schedule. The lower average platform times, more split full-time duties, more part-time duties, greater make-up time-costs, lower overtime penalties and spread premiums in the Cabot Garage optimized schedules may result from any of the following possible reasons. First, because of limitations in the software, Micro is unable to create tighter schedules (higher average platform times) in the MBTA context. Therefore, it has to employ more manpower to cover the blocks and this results in more make-up time-costs than overtime penalties and spread premiums. The difference between produced 3-piece full-time duties may also

[34] As mentioned before, the reported average platform times do not include pull-in and pull-out times.

explain these results. 3-piece FTOs generated in all test schedules are all lower than in the manual schedule by about 10. Because HASTUS could not produce more 3-piece FTOs to cover these pieces of work, more other types of duty (specially PTOs) were required. Alternatively of course, the parameters in the input files may not be set very well and thus restrict (or discourage) HASTUS from producing more satisfactory results.

In contrast, HASTUS works very well for Albany (see *Table 4-7*). Unlike the Cabot case, the initial crew schedules for Albany are very close to the optimized crew schedules and the manual crew schedule except that the number of part-time duties in every base schedule is slightly higher. However, the optimization function corrects this deficiency by forcing the optimized crew schedules to abide by the PTO constraint. It seems that HASTUS can usually produce an acceptable optimized automated crew schedule which has lower total pay hours (by about 1%) than the Albany manual schedule. Aside from fewer straight full-time duties and corresponding lower paid meal breaks as in the Cabot case, the required manpower, the average platform times, and pay hours (for each category) in the optimized crew schedules for Albany are all close to the manual crew schedule. As in the optimized Cabot Garage schedules, the rematch of duties may also force more small pieces of work into regular duties (full-time or part-time duties) to reduce trippers or the number of part-time duties, and thus result in slightly lower average platform times compared with the initial schedules. The optimized Albany Garage crew schedules also have greater total make-up times and lower overtime penalties and spread premiums than the initial schedules. However, unlike Cabot, these factors do not increase required manpower.

Compared with the manual schedule, the optimized Albany Garage schedules also have slightly greater total make-up times and spread premiums and lower overtime penalties. Because the average platform times and required manpower are virtually unchanged in the optimized Albany Garage schedules (compared with the manual schedule), it seemed that HASTUS can produce as productive duties as the manual schedule which contradicts the first hypothesis given above for the Cabot result.

As shown in both tables, the optimized schedules usually have slightly greater total pay hours than the initial schedules for both garages. The optimized Cabot Garage schedules usually have greater total pay hours than the associated manual schedule while the optimized Albany Garage schedules usually have lower total pay hours than the manual schedule. Another interesting statistic is the different total sign-on times in both tables. As mentioned before, this cost includes not only the actual sign-on allowance, but also the pull-in and pull-out times. Because street reliefs are not allowed in Albany, more pull-in and pull-out may occur for every duty. The reported sign-on time thus will increase. As shown in the above two tables, the reported sign-on times are as high as about 17% of the total pay hours for Albany Garage (the manual, initial, or optimized schedules), while it is about 10% of the total pay hours in the Cabot case. More pull-ins and pull-outs in Albany also result in lower reported average platform times for full-time duties (straight or split) for Albany by 30 minutes compared with Cabot.

Because an initial schedule for either Cabot or Albany usually cannot satisfy the work rules, the optimized automated crew schedules for both garages are used as the standard automated crew schedules in the following evaluations.

4.3.2.2 Part-time Operator Wage Rates

As mentioned above, HASTUS allows only one wage rate in the parameter file for each duty type (in this case, full-time and part-time operators). However, the true wage rate for MBTA part-time employees depends on seniority, in effect meaning that the larger the number of the part-time operators, the higher their average wage rate. Because full-time operators are always more senior than part-time operators, the part-time operator wage rate[35] will usually be lower than the full-time operator wage rate. Thus the level of part-time manpower will not only affect the final schedules but also the associated total costs, because the assumed (or nominal) PTO wage rate may not be correct given the solution generated.

Traditionally at the MBTA, the PTO wage rate in the parameter file is set as the minimum PTO wage rate. However, experience (as shown above) shows that HASTUS is inclined to produce more (cheaper) part-time duties than desired at the price of fewer than desired full-time duties, especially for Cabot. If HASTUS can increase the number of full-time duties, the number of part-time runs included in the final schedule should be reduced and an acceptable automated solution may be generated, as desired by the MBTA. Thus, the question of how to select an appropriate PTO wage rate in HASTUS is important for the performance of the automatic crew scheduling function. There are two obvious ways in HASTUS to reduce the number of part-time duties: (1) through varying the PTO wage rate and (2) through varying the constraint on the number of PTO runs allowed. With an appropriate PTO wage rate, HASTUS may produce a better schedule in terms of the manpower (total or the part-time duties) or the total pay hours.

In this section, we examine the PTO wage rate in two ways. First, we focus on the relationship between the PTO wage rate and the total pay hours to see how different PTO wage rates affect the corresponding total pay hours. Because the total cost given by HASTUS is greatly affected by the PTO wage rate, the total pay hours are more appropriate for the evaluation[36]. Second, the relationship between the PTO wage rate and the number of part-time duties is examined to test if the PTO wage rate can be used as a parameter to control the number of part-time duties. These tests can hopefully give us a better idea of the impact that the PTO wage rate may have on the final schedule and also

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[35] It is abbreviated as *the PTO wage rate* in the following sections, while the full-time operator pay rate is abbreviated as *the FTO wage rate.*

[36] The definition of the total pay hours is explained in section 4.2.1.

help to define an appropriate PTO wage rate in the parameter file to influence both the total pay hours and the number of part-time duties. This evaluation is applied to both Cabot Garage and Albany Garage.

Tables 4-8 and *4-9* show the key attributes of the solutions as the part-time operator wage rate varies from \$10 to \$999 dollars per hour for Cabot and Albany respectively. This range of PTO wage rates was chosen bracketing the FTO wage rate to test how the PTO wage rate can influence the number of part-time duties. From these two tables, it is clear that unless the PTO wage rate is as high as \$999, even over a wide range (from \$10 to even \$100) of part-time operator wage rates, the final run cuts are virtually unchanged for either Cabot or Albany. Specifically the number of part-time operators for the tests remain at about 70 for Cabot and 45 for Albany, no matter what the PTO wage rate is. The total pay hours of almost all the tests for Cabot are slightly greater (by about 0.5%) than the manual schedule, and the tests for Albany are slightly lower than that of the manual schedule (by about 1%). The PTO wage rate of \$999 shows some interesting results. With this kind of PTO wage rate, HASTUS would rather not produce any part-time duties and let these small pieces of work become trippers at both garages.

Similarly the other components (the number of duties, platform times, etc.) of the schedules are virtually constant over the PTO wage rate range from \$10 to \$100. This implies that if the part-time wage rate is changed from the lowest rate of \$10.00 to the highest rate of \$100.00 (exclude the wage rate of \$999), it will have no real effect on the final schedules, and hence on the number of part-time duties as well as the true total costs (total pay hours). It appears from this test that the PTO wage rate is not a good parameter to control the number of part-time duties, and it will not affect the total pay hours significantly. From examining the results in *Tables 4-6*, *4-7*, *4-8*, and *4-9*, it is obvious that HASTUS tries to minimize the total cost given the cost parameters. First, the number of straight full-time duties in every test for Cabot is from 15 or 18 compared with 28 in the manual solution and is from 6 to 8 at Albany compared with 13 in the manual solution.

This appears to be because these full-time straight runs are more expensive as a result of the paid meal break. Second, it tries to increase the number of part-time operators for Cabot because of the lack of overtime penalties and spread premiums, and it tries to increase the number of split full-time duties for Albany because they are cheaper than the straight duties.

Table 4-8: Micro Crew Schedules with Different PTO Wage Rates for Cabot Garage

	manual	*Test 1*	*(%)*	*Test 2*	*(%)*	*Test 3*	*(%)*	*Test 4*	*(%)*	*Test 5*	*(%)*	*Test 6*	*(%)*	*Test 7*	*(%)*
PTO wage rate	13.85	10		12		13.85		14		16		18.46		20	
Period length		31		31		31		31		31		31		31	
# of fto-str	28	15	-46.4	17	-39.3	16	-42.9	17	-39.3	16	-42.9	17	-39.3	17	-39.3
2-piece	26	15		17		16		17		16		17		17	
3-piece	2														
Platform time	6h34	6h35		6h29		6h32		6h28		6h31		6h29		6h29	
# of fto-spl	154	167	8.4	167	8.4	166	7.8	166	7.8	167	8.4	169	9.7	169	9.7
2-piece	108	140		145		139		142		142		154		143	
3-piece	42	27		22		27		24		25		15		26	
4-piece	4														
Platform time	7h04	6h44		6h43		6h42		6h46		6h45		6h46		6h43	
# of pto	56	71	26.8	69	23.2	73	30.4	68	21.4	71	26.8	67	19.6	69	23.2
1-piece	2	32		32		36		28		33		30		34	
2-piece	54	39		37		37		39		37		36		35	
3-piece								1		1		1			
Platform time	4h56	4h33		4h32		4h29		4h36		4h29		4h28		4h26	
Total Runs	238	253	6.30	253	6.30	255	7.14	251	5.46	254	6.72	253	6.30	255	7.14
Platform time	6h30.58	6h06.43		6h06.55		6h03.48		6h09.43		6h06.35		6h08.26		6h05.14	
# of extras	0	1		1		1		1		0		0		0	
Platform time	0h00	5h56		5h56		5h56		5h56		0h00		0h00		0h00	
Re. T. platform	1550h53	1546h23		1547h14		1546h10		1546h40		1551h56		1553h36		1552h15	
sign-on/pull	186h06	191h58		192h38		192h03		192h27		191h25		192h34		192h05	
join-up	11h30	4h19		3h25		5h14		5h14		5h21		3h16		5h12	
paid meal	14h05	8h51		11h23		11h10		10h59		9h41		11h54		11h24	
Guaranteed run	3h12	43h58		44h02		44h56		37h45		42h10		40h15		47h38	
Overtime	32h55	7h44		7h45		7h28		9h29		8h53		8h24		8h47	
Spread rate 1	9h44	5h31		6h09		5h24		5h07		4h36		6h36		5h40	
Extra platform	0h00	5h56		5h56		5h56		5h56		0h00		0h00		0h00	
To. pay hour	1808.42	1814.67	0.35	1818.53	0.56	1818.35	0.55	1813.62	0.29	1814.03	0.31	1816.58	0.45	1823.02	0.81

	manual	*Test 8*	*(%)*	*Test 9*	*(%)*	*Test 10*	*(%)*	*Test 11*	*(%)*	*Test 12*	*(%)*	*Test 13*	*(%)*	*Test 14*	*(%)*
PTO wage rate	13.85	22		24		26		28		30		100		999	
Period length		31		31		31		31		31		31		31	
# of fto-str	28	16	-42.9	16	-42.9	17	-39.3	16	-42.9	18	-35.7	16	-42.9	16	-42.9
2-piece	26	16		16		17		16		18		16		16	
3-piece	2														
Platform time	6h34	6h32		6h32		6h32		6h31		6h27		6h32		6h32	
# of fto-spl	154	164	6.5	168	9.1	168	9.1	167	8.4	164	6.5	168	9.1	159	3.2
2-piece	108	138		141		140		140		136		140		131	
3-piece	42	26		27		28		27		28		28		28	
4-piece	4														
Platform time	7h04	6h48		6h44		6h44		6h49		6h50		6h47		6h55	
# of pto	56	73	30.4	69	23.2	69	23.2	70	25.0	70	25.0	70	25.0		
1-piece	2	32		32		32		30		30		34			
2-piece	54	40		37		37		39		40		36			
3-piece		1						1							
Platform time	4h56	4h27		4h29		4h27		4h24		4h24		4h17			
Total Runs	238	253	6.30	253	6.30	254	6.72	253	6.30	252	5.88	254	6.72	175	-26.5
Platform time	6h30.58	6h06.41		6h06.36		6h06.29		6h08.01		6h08.05		6h05.09		6h53.44	
# of extras	0	1		1		0		0		1		1		118	
Platform time	0h00	5h56		5h56		0h00		0h00		5h56		5h56		3h19	
Re. T. platform	1550h53	1546h15		1545h52		1551h28		1551h49		1545h58		1545h51		1206h45	
sign-on/pull	186h06	192h45		192h27		194h48		193h17		193h29		192h39		144h38	
join-up	11h30	5h42		5h39		6h12		5h35		4h44		6h29		5h39	
paid meal	14h05	10h19		11h39		10h17		10h40		10h56		11h09		9h09	
Guaranteed run	3h12	31h18		41h19		42h26		32h31		31h12		39h12		23h14	
Overtime	32h55	11h05		10h42		12h06		16h08		17h06		18h35		28h25	
Spread rate 1	9h44	4h28		6h41		6h21		5h39		6h15		9h04		10h28	
Extra platform	0h00	5h56		5h56		0h00		0h00		5h56		5h56		391h49	
To. pay hour	1808.42	1807.80	-0.03	1820.25	0.65	1823.63	0.84	1815.65	0.40	1815.60	0.40	1828.92	1.13	1820.12	0.65

Table 4-9: Micro Crew Schedules with Different PTO Wage Rates for Albany Garage

	manual	Test 1	(%)	Test 2	(%)	Test 3	(%)	Test 4	(%)	Test 5	(%)	Test 6	(%)	Test 7	(%)
PTO wage rate	13.85	10		12		13.85		14		16		18.46		20	
Period length		34		34		34		34		34		34		34	
# of fto-str	13	7	-46.2	6	-53.8	8	-38.5	7	-46.2	7	-46.2	7	-46.2	7	-46.2
2-piece	13	7		6		8		6		7		7		7	
3-piece								1							
Platform time	6h05	6h04		6h00		5h59		5h54		6h04		5h59		6h00	
# of fto-spl	72	78	8.3	82	13.9	78	8.3	80	11.1	78	8.3	78	8.3	78	8.3
2-piece	57	77		81		77		80		77		77		77	
3-piece	14	1		1		1				1		1		1	
4-piece	1														
Platform time	6h30	6h27		6h26		6h28		6h26		6h28		6h29		6h30	
# of pto	45	45	0.0	42	-6.7	44	-2.2	43	-4.4	45	0.0	45	0.0	45	0.0
1-piece															
2-piece	44	45		42		44		43		45		45		45	
3-piece	1														
Platform time	4h21	4h24		4h19		4h21		4h23		4h24		4h23		4h20	
Total Runs	130	130	0.00	130	0.00	130	0.00	130	0.00	130	0.00	130	0.00	130	0.00
Platform time	5h43.07	5h43.59		5h44.08		5h44.02		5h44.02		5h44.07		5h44.14		5h44.08	
# of extras	0	0		0		0		0		0		0		0	
Platform time	0h00	0h00		0h00		0h00		0h00		0h00		0h00		0h00	
Re. T. platform	743h27	745h18		745h39		745h26		745h26		745h36		745h51		745h39	
sign-on/pull	160h06	154h46		155h04		154h26		153h22		154h27		154h09		154h40	
join-up	4h48	0h15		0h15		0h15		0h15		0h15		0h15		0h15	
paid meal	7h25	3h59		3h25		4h31		4h02		3h59		4h11		3h33	
Guaranteed run	11h35	16h16		20h02		17h35		19h43		16h54		15h49		14h23	
Overtime	8h38	1h53		1h13		2h35		1h29		3h10		2h35		3h53	
Spread rate 1	1h48	4h51		6h19		5h06		6h03		5h25		4h22		4h23	
Extra platform	0h00	0h00		0h00		0h00		0h00		0h00		0h00		0h00	
To. pay hour	937.78	927.3	-1.12	931.95	-0.62	936.90	-0.09	930.33	-0.79	929.77	-0.85	927.20	-1.13	926.77	-1.17

	manual	Test 8	(%)	Test 9	(%)	Test 10	(%)	Test 11	(%)	Test 12	(%)	Test 13	(%)	Test 14	(%)
PTO wage rate	13.85	22		24		26		28		30		100		999	
Period length		34		34		34		34		34		34		34	
# of fto-str	13	6	-53.8	7	-46.2	7	-46.2	8	-38.5	8	-38.5	6	-53.8	9	-30.8
2-piece	13	6		7		7		8		8		6		9	
3-piece															
Platform time	6h05	6h00		6h03		6h03		6h05		5h57		6h00		5h56	
# of fto-spl	72	79	9.7	78	8.3	78	8.3	79	9.7	79	9.7	81	12.5	80	11.1
2-piece	57	78		77		77		78		78		79		79	
3-piece	14	1		1		1		1		1		2		1	
4-piece	1														
Platform time	6h30	6h31		6h33		6h34		6h31		6h31		6h33		6h30	
# of pto	45	45	0.0	45	0.0	45	0.0	43	-4.4	43	-4.4	43	-4.4		
1-piece															
2-piece	44	45		45		45		43		43		43			
3-piece	1														
Platform time	4h21	4h18		4h15		4h14		4h13		4h14		4h08			
Total Runs	130	130	0.00	130	0.00	130	0.00	130	0.00	130	0.00	130	0.00	89	-31.5
Platform time	5h43.07	5h44.06		5h44.13		5h44.12		5h44.19		5h44.11		5h44.12		6h27.18	
# of extras	0	0		0		0		0		0		0		82	
Platform time	0h00	0h00		0h00		0h00		0h00		0h00		0h00		2h40	
Re. T. platform	743h27	745h33		745h50		745h46		746h02		745h45		745h46		574h30	
sign-on/pull	160h06	155h13		155h38		155h13		155h48		154h48		154h45		102h52	
join-up	4h48	0h15		0h15		0h15		0h15		0h15		0h31		0h13	
paid meal	7h25	3h25		3h49		3h49		4h10		4h23		3h25		5h23	
Guaranteed run	11h35	14h29		12h35		12h21		15h16		16h48		15h57		17h52	
Overtime	8h38	5h31		5h11		5h49		6h18		7h16		10h05		5h39	
Spread rate 1	1h48	5h51		5h00		5h16		6h28		8h09		9h39		7h21	
Extra platform	0h00	0h00		0h00		0h00		0h00		0h00		0h00		219h26	
To. pay hour	937.78	930.28	-0.80	928.30	-1.01	928.48	-0.99	934.28	-0.37	935.4	-0.25	940.13	0.25	933.27	-0.48

Obviously, no schedule in these tables was found that was better than the Cabot Garage manual schedule in terms of the number of both part-time duties and total runs, and the average platform times for both split full-time duties and part-time duties. Every test seriously violated the part-time manpower constraint which conflicts with the desire of the MBTA to keep the part-time manpower requirement low. It was inclined to employ more manpower (especially part-time duties) to lower overtime penalties or even spread premiums which resulted in unacceptable required manpower (part-time duties and total runs). Higher required manpower may also result from HASTUS being unable to produce a tighter and more productive machine schedule with higher platform times and lower unproductive make-up times. The low average platform times of the split full-time duties and the part-time duties explains why these tests required more manpower. For this part of the evaluation, HASTUS-Micro seemed unable to produce a better acceptable automatic optimized schedule than the manual schedule for the Cabot Garage.

In contrast, the evaluation in *Table 4-9* for Albany Garage produced quite different results. Unlike Cabot Garage, Micro consistently generated extremely good automatic optimized crew schedules for Albany Garage. Almost every schedule in *Table 4-9* is at least as good as the manual schedule in terms of the manpower constraints (for all duty types), the platform times, and the total pay hours.

Although there is no great difference among the resulting schedules for different PTO wage rates, *Test 4* in *Table 4-6* seems to have the smallest number of total runs with comparatively low part-time duties. Therefore, the PTO wage rate of $14 was chosen as the base PTO wage rate for the Cabot Garage parameter files used in the following sections. In the Albany case, the PTO rate of $16 was chosen because its parameter file produced comparatively low total pay hours with comparatively high average total platform times.

4.3.2.3 Part-time Operator Constraints

Since the PTO wage rate seems unable to control the number of part-time duties, the PTO constraint then was used to examine if the number of part-time duties in automated crew schedules (specially for Cabot) could be reduced. As shown in *Table 4-10*, the maximum allowed number of PTOs was lowered from 56 to 50 for Cabot and from 45 to 40 for Albany. We also used different PTO wage rates to strengthen the control over the number of part-time duties.

Table 4-10: Micro Schedules with Different PTO Wage Rates vs. PTO Constraints

1. Cabot

	manual	Base 1	(%)	Test 1	(%)	Base 2	(%)	Test 2	(%)	Base 3	(%)	Test 3	(%)
PTO wage rate	13.85	10		10		20		20		30		30	
PTO constraint		0-56		0-50		0-56		0-50		0-56		0-50	
Period length		31		31		31		31		31		31	
# of flo-str	28	15	-46.4	15	-46.4	17	-39.3	17	-39.3	18	-35.7	18	-35.7
2-piece	26	15		15		17		17		18		18	
3-piece	2												
Platform	6h34	6h35		6h35		6h29		6h28		6h27		6h27	
# of flo-spl	154	167	8.4	167	8.4	169	9.7	168	9.1	164	6.5	164	6.5
2-piece	108	140		140		143		142		136		136	
3-piece	42	27		27		26		26		28		28	
4-piece	4												
Platform	7h04	6h44		6h44		6h43		6h43		6h50		6h50	
# of pto	56	71	26.8	71	26.8	69	23.2	69	23.2	70	25.0	70	25.0
1-piece	2	32		32		34		34		30		30	
2-piece	54	39		39		35		35		40		40	
3-piece													
Platform	4h56	4h33		4h33		4h26		4h26		4h24		4h24	
Total Runs	238	253	6.30	253	6.30	255	7.14	254	6.72	252	5.88	252	5.88
Platform	6h30.58	6h06.43		6h06.43		6h05.14		6h05.21		6h08.05		6h08.05	
# of extras	0	1		1		0		1		1		1	
Platform	0h00	5h56		5h56		0h00		5h56		5h56		5h56	
Re. T. platform	1550h53	1546h23		1546h23		1552h15		1546h43		1545.58		1545h58	
sign-on/pull	186h06	191h58		192h03		192h05		190h57		193h29		193h24	
join-up	11h30	4h19		4h19		5h12		5h12		4h44		4h44	
paid meal	14h05	8h51		9h39		11h24		11h14		10h56		10h56	
Guaranteed run	3h12	43h58		43h05		47h38		47h10		31h12		31h17	
Overtime	32h55	7h44		7h44		8h47		8h51		17h06		17h06	
Spread rate 1	9h44	5h31		5h31		5h40		5h41		6h15		6h15	
Extra platform	0h00	5h56		5h56		0h00		5h56		5h56		5h56	
To. pay hour	1808.42	1814.67	0.35	1814.67	0.35	1823.02	0.81	1821.73	0.74	1815.60	0.40	1815.60	0.40

2. Albany

	manual	Base 1	(%)	Test 1	(%)	Base 2	(%)	Test 2	(%)	Base 3	(%)	Test 3	(%)
PTO wage rate	13.85	10		10		20		20		30		30	
PTO constraint		0-45		0-40		0-45		0-40		0-45		0-40	
Period length		34		34		34		34		34		34	
# of flo-str	13	7	-46.2	8	-38.5	7	-46.2	8	-38.5	8	-38.5	8	-38.5
2-piece	13	7		8		7		8		8		8	
3-piece													
Platform	6h05	6h04		5h58		6h00		5h59		5h57		5h58	
# of flo-spl	72	78	8.3	79	9.7	78	8.3	79	9.7	79	9.7	80	11.1
2-piece	57	77		78		77		78		78		79	
3-piece	14	1		1		1		1		1		1	
4-piece	1												
Platform	6h30	6h27		6h26		6h30		6h28		6h31		6h30	
# of pto	45	45	0.0	43	-4.4	45	0.0	43	-4.4	43	-4.4	42	-6.7
1-piece													
2-piece	44	45		43		45		43		43		42	
3-piece	1												
Platform	4h21	4h24		4h24		4h20		4h19		4h14		4h13	
Total Runs	130	130	0.00	130	0.00	130	0.00	130	0.00	130	0.00	130	0.00
Platform	5h43.07	5h43.59		5h44.03		5h44.08		5h44.11		5h44.11		5h44.12	
# of extras	0	0		0		0		0		0		0	
Platform	0h00	0h00		0h00		0h00		0h00		0h00		0h00	
Re. T. platform	743h27	745h18		745h27		745h39		745h45		745h45		745h47	
sign-on/pull	160h06	154h46		153h58		154h40		154h07		154h48		155h08	
join-up	4h48	0h15		0h18		0h15		0h18		0h15		0h15	
paid meal	7h25	3h59		4h36		3h33		4h31		4h23		4h33	
Guaranteed run	11h35	16h16		19h30		14h23		17h11		16h48		19h08	
Overtime	8h38	1h53		1h18		3h53		3h56		7h16		6h40	
Spread rate 1	1h48	4h51		6h33		4h23		5h36		6h09		6h29	
Extra platform	0h00	0h00		0h00		0h00		0h00		0h00		0h00	
To. pay hour	937.78	927.30	-1.12	931.67	-0.65	926.77	-1.17	931.40	-0.68	935.40	-0.25	938.00	0.02

PTO constraint: Minimum and maximum allowed part-time operators defined in the parameter file (PTO duty type).

It seems that different PTO constraints combined with different PTO wage rates have little impact on automated crew schedules. The final automated crew schedules are virtually unchanged for Cabot. For Albany, this constraint does reduce the number of part-time duties by 1 or 2. However, total runs in every test remain at 130. *Table 4-10* also shows that the PTO constraint in the parameter file is treated like a soft constraint in HASTUS which may be ignored. For Cabot, it has not yet been possible to satisfy this constraint.

4.3.2.4 Period Lengths

As mentioned in *section 4.1*, different period lengths will affect the way Macro cuts the blocks as well as the way it matches pieces of work, and may result in different costs and different Micro schedules. Therefore, the impact of different period lengths on Macro and Micro schedules is examined in this section. The consistency between different Macro schedules and corresponding Micro schedules is also addressed. If changes in total pay hours, total manpower or other important values in the Macro schedules are not consistent with the final Micro schedules, it implies that Macro schedules cannot be used to predict the impacts of potential changes, because they will not indicate what the corresponding final crew schedules would be. Hopefully, suitable period lengths for both garages can be found.

The Macro files shown in *Appendix C* were used as base files for both garages. All other Macro files tested in this part are the same as these two Macro files[37] except that the values defined in each Macro file are modified to be consistent with each period length. Apart from a Macro file, parameter and cutting files are also required for the Macro function[38]. The cutting files used in the previous sections were still used in this part

[37] The Albany macro file used in this part is slightly different from that in the first part. The number-pieces parameter (the 62nd constraint) was changed from (2 2) to (1 2) to allow one-piece part-time duties to be generated.

[38] The selection file is not required for the Macro function.

of the evaluation. Based on the discussion of the results in the previous part, parameter files with PTO wage rates of $14 per hour for Cabot Garage and $16 per hour for Albany Garage were chosen. In fact, parameter files with different PTO wage rates will not significantly affect the Macro results for either Cabot Garage and Albany Garage. For example, the Cabot Macro file was tested using two parameter files (one with PTO wage rates of $14 and $13.85) with identical Macro results resulting (*Test 6* in *Table 4-11*). Identical results were also found for Albany Garage for the parameter files in which the PTO rates are $16 and $18.46 (*Test 8* in *Table 4-13*).

It turns out that for Cabot Garage, period lengths that are less than 32 minutes will produce too many variables (possible duty types) for Macro to handle (at most 2900 variables). Therefore, some constraints, which were originally designed to be as close to the real conditions (the manual schedule) as possible, have to be tightened to reduce the number of variables. Stricter constraints can reduce the options for cutting the blocks and matching the pieces. For example, a 3-piece full-time duty type in the Macro files for Cabot Garage usually creates too many variables, As a result the Macro file has to be adjusted by narrowing the range-start-time (the period in which such a duty can start) constraint, the mealbreak-length constraint, and the piece-length constraint to make Macro feasible. In the Cabot Garage case, the second range-start-time constraint (the 47th constraint in *Appendix C5*) was therefore narrowed from the range of 10h20 to 14h28 to the range of 10h20 to 12h55. The mealbreak-length constraint (the 51st constraint) was tightened from the range of 1h33 to 4h08 to the range of 1h33 to 2h35. The piece-length constraint (the 54th constraint) was narrowed from the range of 2h04 to 5h10 to the range of 2h04 to 4h08. These adjustments are not only applied to this kind of Macro file (with 6 duty types) for Cabot Garage, but also other Macro files with different structures. The Macro files with period lengths of 26 and 28 minutes, which were identical to *Appendix C10* (3 duty types) except that the PTO max-number-drivers constraint (the 69th constraint) was relaxed to 56, were tested for Cabot Garage. They also needed similar adjustments for use in the Cabot Garage case.

Longer period lengths may also produce problems. For period lengths greater than 31 minutes, we may have to adjust (loosen) the constraints originally designed to prevent the generation of trippers, such as allowing a longer maximum length for a tripper. For example, the tripper-max-length constraint (the 92nd constraint) usually has to be set higher than 4h00 for longer period lengths. Otherwise, Macro may not work. The same problem did not arise when the Albany Garage Macro files[39] with period lengths of 34 or 36 minutes were used in the Cabot Garage case.

Another important issue concerns the generation of trippers. In order to produce Macro schedules to satisfy the work rules, trippers must be eliminated. In Micro, an optimization function is available for the elimination of trippers, but not in Macro. Therefore, we could relax the constraints (extend permissible ranges for the cutting and matching) for all period lengths in Cabot Garage, so that Macro will have more options to cut pieces and facilitate their matching in duties without generating trippers. For example, with the period length of 34 minutes, if the duty-length constraints of the early and late split full-time duty types (the 34th and 66th constraints in *Appendix C5*) are set as 7h56 in the Cabot Garage Macro file, 20.45 extras with 74.4 hours will be generated in the Macro schedule. When these constraints are relaxed to 8h30 (in the base Macro schedule), no extra will be created in the Macro file (the schedules of *Base 2* and *Test 2-1* in *Tables 4-16* in *section 4.3.3.2* shows these results for Cabot Garage). Trippers are not usually generated in either Macro or Micro schedules for Albany Garage. Except for the duty-length parameter, other parameters such as the guaranteed-piece constraint can also be relaxed to help eliminate trippers.

[39] The PTO manpower constraint was adjusted as above.

Fortunately, the difficulties mentioned above do not affect the Macro files for Albany Garage under current conditions (current input files, parameter files, etc.), simply because the problem size for Albany is smaller. There are 238 duties required in Cabot Garage, while only 130 duties are needed in Albany Garage. Besides, Macro has to try a tremendous number of possible cutting and matching opportunities to combine around 460 pieces of work into 225 duties (in a Macro schedule, not a final Micro schedule) for Cabot Garage (see *Table 4-11*). There are only about 240 pieces of work and 125 duties in a Macro schedule for Albany Garage (see *Table 4-13*). These differences make the crew scheduling process for Albany Garage much easier and do not create as many problems as for Cabot Garage.

Cabot Macro vs. Micro schedules: *Tables 4-11* and *4-12* show the Macro results and the corresponding Micro results for 11 different period lengths from 26 minutes to 40 minutes for Cabot Garage. From *Table 4-11*, the Macro schedules are basically the same for different period lengths. Unlike the Cabot Micro schedules produced in the previous sections, almost all Macro schedules are acceptable and satisfy the work rules and the manpower constraints. No trippers were produced, and the total runs in all Macro schedules were lower than the manual schedule (ranging from 219 to 235) while keeping the number of part-time duties (52 to 56, except for the Macro file with the period length of 31 minutes) below the upper limit (56). The average duty lengths, and spreads for different duty types compare very well with the constraints[40]. Some average duty lengths were higher than the work rules, such as 8h30 in the Macro file with period length of 34 minutes, because of the selection of duty length parameter. This issue will be discussed in more detail in the later sections of this chapter.

40 These explain why the manpower is lower than the manual schedule.

Table 4-11: Period Lengths for Cabot Garage: Macro Schedules

	manual	Test 1	(%)	Test 2	(%)	Test 3	(%)	Test 4	(%)	Test 5	(%)	Test 6	(%)	Test 7	(%)
PTO wage rate	13.85	14		14		14		14		14		14		14	
Period length		26		27		28		29		30		31		32	
# of fto-str	28	15	-46.4	15	-46.4	15	-46.4	15	-46.4	15	-46.4	15	-46.4	15	-46.4
Platform time	6h34														
# of fto-spl	154	155.82	1.2	158.54	2.9	163	5.8	162	5.2	164	6.5	156.46	1.6	158.33	2.8
Platform time	7h04														
# of early		66.14		65.77		54		54		59		55		62.33	
Duty length		8h14		8h06		7h56		8h13		8h00		8h16		8h00	
Spread		9h52		10h15		9h18		9h33		9h25		9h17		9h29	
# of 3-piece		35.95		39		29		30		30		36.77		32.67	
Duty length		7h15		7h31		6h49		6h42		6h43		6h59		7h14	
Spread		9h10		9h43		8h52		8h55		8h44		9h26		9h28	
# of late		53.73		53.77		80		78		75		64.69		63.33	
Duty length		8h14		8h06		7h56		8h13		8h00		8h16		8h00	
Spread		9h16		9h07		8h47		9h01		8h52		9h05		9h10	
# of pto	56	56	0.0	52.23	-6.7	56	0.0	56	0.0	56	0.0	59.27	5.8	56	0.0
Platform time	4h56														
Duty length		5h38		5h51		6h04		6h17		6h00		5h41		5h52	
Spread		12h28		12h33		12h20		12h32		12h24		12h21		12h41	
Total Runs	238	226.82	-4.70	225.77	-5.14	234	-1.68	233	-2.10	235	-1.26	230.73	-3.05	229.33	-3.64
Platform time	6h30.58														
Duty length		7h23		7h26		7h19		7h31		7h19		7h20		7h19	
Spread		10h17		10h26		9h50		10h02		9h54		10h05		10h13	
# of extras	0	0		0		0		0		0		0		0	
Worked hrs		1558.3		1561.9		1562.9		1561.7		1552		1561.9		1559.5	
hrs in extras		0		0		0		0		0		0		0	
hrs in Guaranted		19.8		9.3		5.91		11.8		7.5		18.2		12	
hrs in overtime		20.5		12.8		3		20.1		7.5		25		6.8	
hrs of paid break		1.7		1.8		12.6		10.2		11		9		4.8	
hrs in spread		3.7		4.5		0		0		0		0		2.2	
To. pay hour	1808.42	1604.00	-11.3	1590.30	-12.1	1584.41	-12.4	1603.80	-11.3	1578.00	-12.7	1614.10	-10.7	1585.30	-12.3
# of pieces		462.00		461.00		467.00		467.00		469.00		466.00		459.00	

	manual	Test 8	(%)	Test 9	(%)	Test 10	(%)	Test 11	(%)
PTO wage rate	13.85	14		14		14		14	
Period length		34		36		38		40	
# of fto-str	28	15	-46.4	15	-46.4	15	-46.4	15	-46.4
Platform time	6h34								
# of fto-spl	154	148.84	-3.4	158	2.6	156.31	1.5	157.81	2.5
Platform time	7h04								
# of early		59.42		25.5		46.63		61.49	
Duty length		8h30		8h24		8h14		8h00	
Spread		10h08		9h49		9h26		9h16	
# of 3-piece		43.16		67.5		56.05		31.2	
Duty length		7h22		7h07		7h35		7h08	
Spread		10h01		9h38		10h07		9h26	
# of late		46.26		65		53.63		65.12	
Duty length		8h30		8h24		8h14		8h00	
Spread		9h28		9h11		9h19		9h03	
# of pto	56	56	0.0	56	0.0	55.32	-1.2	56	0.0
Platform time	4h56								
Duty length		6h14		6h00		5h42		6h00	
Spread		12h42		12h35		12h29		12h33	
Total Runs	238	219.84	-7.63	229	-3.78	226.63	-4.78	228.81	-3.86
Platform time	6h30.58								
Duty length		7h38		7h22		7h24		7h21	
Spread		10h40		10h18		10h23		10h05	
# of extras	0	0		0		0		0	
Worked hrs		1563.4		1561.2		1558		1552.7	
hrs in extras		0		0		0		0	
hrs in Guaranted		23.7		42.4		17.4		13.8	
hrs in overtime		31.7		22.6		17.4		6.7	
hrs of paid break		0		6		0.6		5.7	
hrs in spread		6.3		1.5		6.9		3.1	
To. pay hour	1808.42	1625.10	-10.1	1633.70	-9.7	1600.30	-11.5	1582.00	-12.5
# of pieces		453.00		495.00		479.00		459.00	

# of fto-str: Number of full-time straight duties
# of fto-spl: Number of full-time split duties
# of early: Number of full-time early split duties
# of 3-piece: Number of 3-piece full-time split duties
# of late: Number of full-time late split duties
# of pto: Number of part-time duties
Platform time: Average platform time
Duty length: Average duty length
Spread: Average spread

Worked hrs: Number of worked hours
hrs in extras: Number of hours in extras
hrs in Guaranteed: Number of hours in guaranteed runs
hrs in overtime: Number of hours in overtime penalties
hrs of paid break: Number of hours of paid breaks
hrs in spread: Number of hours in spread premiums

To. pay hour: Total pay hour
# of pieces: Number of constructed pieces of work

The Macro file has a similar problem as the parameter file: in terms of wage rates, and so we still use the total pay hours instead of the reported total cost in the Macro file to reflect the actual cost. However, the components of time-costs available (see *Table 4-11* from *Worked hrs* to *hrs in spread*) in the Macro file are different from those in the Micro file. Specifically there are no *sign-on* or *join-up* time-costs in the Macro file. The total pay hours shown in *Table 4-11* (and other Macro tables) is the sum of these available time-costs. This also explains why the total pay hours in all Macro schedules for Cabot Garage are lower than in the manual schedule by about 200 hours (about 13% of the total pay hours).

Table 4-12: Period Lengths for Cabot Garage: Micro Schedules

	manual	Test 1	(%)	Test 2	(%)	Test 3	(%)	Test 4	(%)	Test 5	(%)	Test 6	(%)
PTO wage rate	13.85	14		14		14		14		14		14	
Period length		26		27		28		29		30		31	
# of flo-str	28	15	-46.4	17	-39.3			17	-39.3	19	-32.1	17	-39.3
2-piece	26	15		17				17		19		17	
3-piece	2												
Platform time	6h34	6h35		6h32				6h29		6h23		6h28	
# of flo-spl	154	171	11.0	171	11.0			168	9.1	165	7.1	166	7.8
2-piece	108	154		159				145		142		142	
3-piece	42	17		12				23		23		24	
4-piece	4												
Platform time	7h04	6h48		6h49				6h41		6h47		6h46	
# of pto	56	61	8.9	58	3.6			68	21.4	66	17.9	68	21.4
1-piece	2	18		16				32		25		28	
2-piece	54	43		41				36		41		39	
3-piece				1								1	
Platform time	4h56	4h46		4h46				4h30		4h37		4h36	
Total Runs	238	247	3.78	246	3.36			253	6.30	250	5.04	251	5.46
Platform time	6h30.58	6h17.10		6h19.13				6h05.34		6h11.05		6h09.43	
# of extras	0	0		0				2		1		1	
Platform time	0h00	0h00		0h00				5h56		5h56		5h56	
Re. T. platform	1550h53	1552h42		1554h51				1541h31		1546h12		1546h40	
Sign-on/pull	186h06	187h58		189h30				191h45		190h50		192h34	
Join-up	11h30	3h57		3h12				4h45		4h07		5h32	
Paid meal	14h05	9h50		10h50				11h33		14h49		10h39	
Guaranteed run	3h12	37h57		36h57				48h49		39h06		37h39	
Overtime	32h55	9h49		14h47				8h12		10h10		9h26	
Spread rate 1	9h44	6h37		10h19				8h55		6h52		5h10	
Extra platform	0h	0h00		0h00				11h53		5h56		5h56	
To. pay hour	1808.42	1808.83	0.02	1820.43	0.66			1827.38	1.05	1818.03	0.53	1813.60	0.29

	manual	Test 7	(%)	Test 8	(%)	Test 9	(%)	Test 10	(%)	Test 11	(%)
PTO wage rate	13.85	14		14		14		14		14	
Period length		32		34		36		38		40	
# of flo-str	28	16	-42.9	16	-42.9	15	-46.4	15	-46.4	17	-39.3
2-piece	26	16		16		15		15		17	
3-piece	2										
Platform time	6h34	6h33		6h31		6h35		6h35		6h28	
# of flo-spl	154	170	10.4	170	10.4	171	11.0	174	13.0	170	10.4
2-piece	108	153		151		124		135		156	
3-piece	42	17		19		47		39		13	
4-piece	4									1	
Platform time	7h04	6h43		6h46		6h40		6h41		6h46	
# of pto	56	67	19.6	64	14.3	65	16.1	63	12.5	62	10.7
1-piece	2	30		24		27		30		22	
2-piece	54	37		40		36		33		40	
3-piece						2					
Platform time	4h56	4h33		4h39		4h36		4h32		4h40	
Total Runs	238	253	6.30	250	5.04	251	5.46	252	5.88	249	4.62
Platform time	6h30.58	6h08.17		6h12.39		6h08.15		6h09.15		6h14.04	
# of extras	0	0		0		1		0		0	
Platform time	0h00	0h00		0h00		5h59		0h00		0h00	
Re. T. platform	1550h53	1552h59		1552h46		1540h34		1550h51		1552h24	
Sign-on/pull	186h06	189h41		190h49		200h48		193h43		193h55	
Join-up	11h30	3h38		3h39		7h43		5h07		2h35	
Paid meal	14h05	10h04		11h02		9h57		11h04		10h14	
Guaranteed run	3h12	50h07		39h32		44h37		47h30		38h42	
Overtime	32h55	8h42		8h28		8h00		7h15		9h14	
Spread rate 1	9h44	3h40		8h47		6h46		6h49		6h42	
Extra platform	0h	0h00		0h00		5h59		0h00		0h00	
To. pay hour	1808.42	1818.85	0.58	1815.05	0.37	1824.40	0.88	1822.32	0.77	1813.77	0.30

The time-costs shown in the manual schedule and every test schedule in *Table 4-12*, show the sum of the *sign-on/pull-in/pull-out* cost and the *join-up* cost is indeed about 200 hours. This lack of sign-on allowances, pull-in and pull-out costs, and paid join-up costs in the Macro schedule also implies that if Macro is used to estimate the cost impact for any change, this built-in difference will always exist and must be accounted for.

The next issue is the consistency between the Macro schedules and the corresponding Micro schedules. From *Table 4-12*, it appears that these Micro schedules are totally different from the corresponding Macro schedules. All the acceptable Macro schedules now result in quite different and unacceptable Micro schedules just as those shown in previous sections. The number of part-time operators required in all tests is unacceptably high, as is the total required manpower. In addition, the average platform times for split full-time duties, part-time duties, and the total manpower in the automated crew schedules (Micro schedules) are always lower than those in the manual schedule. It seems that Micro cannot produce as productive a set of duties as the manual schedule under current conditions (parameters, input files, etc.). Finally, the total pay hours in the Micro schedules are all slightly greater than the manual schedule.

Figure 4-1 shows that there is little variation in Micro total pay hours but there is greater variation in Micro total required duties generated. However, there is little correlation evident in any of these measures between the Macro and Micro results.

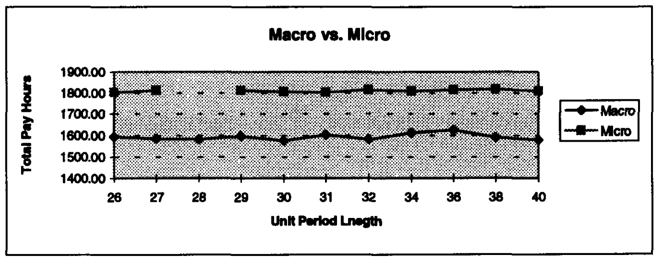
It is interesting to note that although the Macro file with a period length of 28 minutes is feasible, no results were produced for this period length in Micro. We tried three other feasible Macro files with the same period length. The first two Macro files simply adjusted the fringe-benefit parameters of duty types while the last Macro file used the same Macro file as for Albany in *Appendix C10* except for several necessary adjustments[41]. These Macro files also produced feasible Macro schedules, but Micro still neither cuts the blocks nor creates duties.

Since no period length can be identified as clearly superior for Cabot and no acceptable Micro schedule is found in *Table 4-12*, the Micro schedule with the period length of 27 minutes, which has the minimum total runs and minimum number of part-time duties, is chosen as the base schedule for Cabot in the following evaluation.

Figure 4-1: Comparison between Macro and Micro Schedules for Cabot Garage

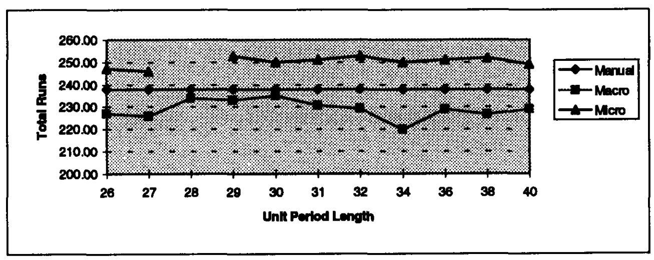
A. Total Pay Hours

Period	Macro	Micro
26	1604.00	1808.83
27	1590.30	1820.43
28	1584.41	
29	1603.80	1827.38
30	1578.00	1818.03
31	1614.10	1813.60
32	1585.30	1818.85
34	1625.10	1815.05
36	1633.70	1824.40
38	1600.30	1822.32
40	1582.00	1813.77



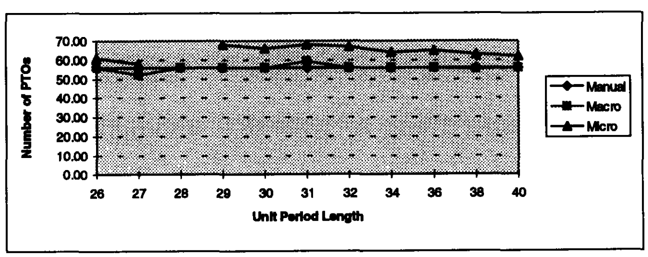
B. Total Runs

Period	Manual	Macro	Micro
26	238.00	226.82	247.00
27	238.00	225.77	246.00
28	238.00	234.00	
29	238.00	233.00	253.00
30	238.00	235.00	250.00
31	238.00	230.73	251.00
32	238.00	229.33	253.00
34	238.00	219.84	250.00
36	238.00	229.00	251.00
38	238.00	226.63	252.00
40	238.00	228.81	249.00



C. Number of PTOs

Period	Manual	Macro	Micro
26	56.00	56.00	61.00
27	56.00	52.23	58.00
28	56.00	56.00	
29	56.00	56.00	68.00
30	56.00	56.00	66.00
31	56.00	59.27	68.00
32	56.00	56.00	67.00
34	56.00	56.00	64.00
36	56.00	56.00	65.00
38	56.00	55.32	63.00
40	56.00	56.00	62.00



[41] Full-time split duty type: The max-spread constraint (the 36th constraint) was relaxed from 7h56 to 8h24. The duty-length constraint (the 46th constraint) was relaxed from 7h28 to 7h56. Part-time duty type: The range-start constraint (the 61st constraint) was relaxed from (5h08-7h56) to (5h08-8h24). The max-number-drivers constraint (the 69th constraint) was relaxed from 45 to 56.

Albany Macro vs. Micro schedules: *Tables 4-13* and *4-14* show the Macro results and the corresponding Micro results for 11 different period lengths ranging from 26 minutes to 40 minutes for Albany Garage. As with Cabot Garage, total pay hours in the Macro schedules are all lower than the manual schedule (by about 100 hours or 13%) because the sign-on costs, pull-in and pull-out costs, and join-up costs are not included.

Table 4-13: Period Lengths for Albany Garage: Macro Schedules

	manual	Test 1	(%)	Test 2	(%)	Test 3	(%)	Test 4	(%)	Test 5	(%)	Test 6	(%)	Test 7	(%)
PTO wage rate	13.85	16		16		16		16		16		16		16	
Period length		26		27		28		29		30		31		32	
# of fto-str	13	5	-61.5	5	-61.5	5	-61.5	7	-46.2	5	-61.5	5	-61.5	5	-61.5
Platform time	6h05														
Duty length								7h15							
Spread								7h44							
# of fto-spl	72	75.94	5.5	76.53	6.3	74.93	4.1	74.26	3.1	72.43	0.6	72.5	0.7	74.62	3.6
Platform time	6h30														
# of fto-spl (2)	57	73.94		71.53		70.93		73.53		69.43		69.5		73.62	
# of fto-spl (3)	14	2		5		4		0.73		3		3		1	
# of fto-spl (4)	1														
Duty length		6h55		6h43		6h59		6h46		6h59		7h13		6h56	
Spread		9h30		9h09		9h23		9h26		9h10		9h28		9h23	
# of pto	45	45	0.0	45	0.0	45	0.0	45	0.0	45	0.0	45	0.0	45	0.0
Platform time	4h21														
Duty length		5h37		5h51		5h35		5h48		5h59		5h41		5h52	
Spread		12h01		12h23		12h19		12h10		12h24		12h33		12h07	
Total Runs	130	125.94	-3.12	126.53	-2.67	124.93	-3.90	126.26	-2.88	122.43	-5.82	122.5	-5.77	124.62	-4.14
Platform time	5h43.07														
Duty length		6h26		6h24		6h27		6h25		6h36		6h38		6h32	
Spread		10h26		10h21		10h29		10h25		10h24		10h39		10h24	
# of extras	0	0		0		0		0		0		0		0	
Worked hrs		778.3		777.1		773.7		777.7		774.5		778.6		780.8	
hrs in extras		0		0		0		0		0		0		0	
hrs in Guaranted		64.9		76.2		54.5		66.2		59.9		32.1		65	
hrs in overtime		0		0		0.1		0		0		0		0	
hrs of paid break		0.9		3.2		2.8		1.3		2		2.6		0.5	
hrs in spread		0		0		0		0		2.3		0.1		0.7	
To. pay hour	937.38	844.10	-10.0	856.50	-8.6	831.10	-11.3	845.20	-9.8	838.70	-10.5	813.40	-13.2	847.00	-9.6
# of pieces		244.00		248.00		246.00		244.00		238.00		237.00		240.00	

	manual	Test 8	(%)	Test 9	(%)	Test 10	(%)	Test 11	(%)
PTO wage rate	13.85	16		16		16		16	
Period length		34		36		38		40	
# of fto-str	13	5	-61.5	5	-61.5	5	-61.5	5	-61.5
Platform time	6h05								
Duty length									
Spread									
# of fto-spl	72	77.33	7.4	77.36	7.4	75	4.2	75.72	5.2
Platform time	6h30								
# of fto-spl (2)	57	75.33		77.36		74		74.45	
# of fto-spl (3)	14	2				1		1.27	
# of fto-spl (4)	1								
Duty length		6h47		6h36		6h57		6h39	
Spread		9h17		9h11		9h12		9h17	
# of pto	45	45	0.0	45	0.0	45	0.0	45	0.0
Platform time	4h21								
Duty length		5h40		6h00		5h42		6h00	
Spread		12h24		12h20		12h31		12h36	
Total Runs	130	127.33	-2.05	127.36	-2.03	125	-3.85	125.72	-3.29
Platform time	5h43.07								
Duty length		6h22		6h23		6h29		6h25	
Spread		10h26		10h21		10h26		10h31	
# of extras	0	0		0		0		0	
Worked hrs		779.7		780.6		778.4		774	
hrs in extras		0		0		0		0	
hrs in Guaranted		74.2		87		55.5		76.5	
hrs in overtime		0.1		0		0		0	
hrs of paid break		1.1		0		0.6		0.8	
hrs in spread		0		0		0.3		0	
To. pay hour	937.38	855.10	-8.8	867.60	-7.4	834.80	-10.9	851.30	-9.2
# of pieces		247.00		246.00		241.00		245.00	

# of fto-str: Number of full-time straight duties
Platform time: Average platform time
Duty length: Average duty length
Spread: Average spread length
# of fto-spl: Number of full-time split duties

# of fto-spl (2): Number of full-time 2-piece split duties
# of fto-spl (3): Number of full-time 3-piece split duties
# of fto-spl (4): Number of full-time 4-piece split duties

# of pto: Number of part-time duties

To. pay hour: Total pay hour
# of pieces: Number of constructed pieces of work

Also as with Cabot, all Macro files for Albany produce duties closely matching the manual schedule. For example, all Macro files produce schedules with lower total runs (122 to 127 compared with 130 for the manual schedule) while keeping the part-time manpower at 45.

Table 4-14: Period Lengths for Albany Garage: Micro Schedules

	manual	Test 1	(%)	Test 2	(%)	Test 3	(%)	Test 4	(%)	Test 5	(%)	Test 6	(%)
PTO Wage rate	13.85	16		16		16		16		16		16	
Period length		26		27		28		29		30		31	
# of flo-str	13	7	-46.2	6	-53.8	9	-30.8	7	-46.2	6	-53.8	5	-61.5
2-piece	13	7		6		8		7		5		5	
3-piece						1				1			
Platform time	6h05	5h58		6h03		6h00		5h54		5h56		6h02	
# of flo-spl	72	77	6.9	80	11.1	75	4.2	76	5.6	78	8.3	80	11.1
2-piece	57	77		79		75		76		76		78	
3-piece	14			1						2		2	
4-piece	1												
Platform time	6h30	6h32		6h28		6h29		6h30		6h31		6h31	
# of pto	45	46	2.2	44	-2.2	46	2.2	46	2.2	45	0.0	45	0.0
1-piece													
2-piece	44	46		44		46		46		45		45	
3-piece	1												
Platform time	4h21	4h20		4h19		4h25		4h20		4h22		4h17	
Total Runs	130	130	0.00	130	0.00	130	0.00	129	-0.77	129	-0.77	130	0.00
Platform time	5h43.07	5h43.43		5h44.00		5h43.43		5h42.16		5h45.02		5h44.01	
# of extras	0	0		0		0		2		2		0	
Platform time	0h00	0h00		0h00		0h00		5h02		1h47		0h00	
Re. T. platform	743h27	744h44		745h22		744h45		735h54		741h51		745h23	
Sign-on/pull	160h06	156h07		154h35		154h52		153h30		153h50		155h04	
Join-up	4h48	0h00		0h20		0h17		0h00		0h54		1h10	
Paid meal	7h25	4h01		4h38		4h53		4h37		3h38		2h39	
Guaranteed run	11h35	12h41		16h11		16h07		15h54		13h02		12h42	
Overtime	8h38	2h45		3h14		3h26		2h22		1h47		3h04	
Spread rate 1	1h48	3h49		4h55		4h18		4h12		4h45		6h09	
Extra platform	0h00	0h00		0h00		0h00		10h04		3h34		0h00	
To. pay hour	937.38	924.12	-1.41	929.25	-0.87	928.63	-0.93	926.55	-1.16	923.35	-1.50	926.18	-1.19

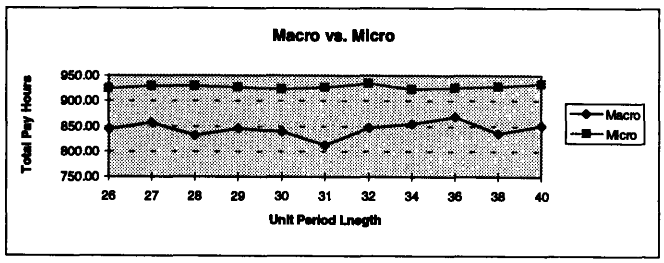
	manual	Test 7	(%)	Test 8	(%)	Test 9	(%)	Test 10	(%)	Test 11	(%)
PTO Wage rate	13.85	16		16		16		16		16	
Period length		32		34		36		38		40	
# of flo-str	13	7	-46.2	8	-38.5	7	-46.2	8	-38.5	8	-38.5
2-piece	13	7		8		7		8		8	
3-piece											
Platform time	6h05	5h53		5h55		5h55		5h55		6h06	
# of flo-spl	72	80	11.1	75	4.2	78	8.3	77	6.9	78	8.3
2-piece	57	79		74		77		77		78	
3-piece	14	1		1		1					
4-piece	1										
Platform time	6h30	6h27		6h35		6h31		6h32		6h27	
# of pto	45	43	-4.4	47	4.4	45	0.0	45	0.0	44	-2.2
1-piece											
2-piece	44	43		47		45		45		44	
3-piece	1										
Platform time	4h21	4h21		4h19		4h19		4h18		4h22	
Total Runs	130	130	0.00	130	0.00	130	0.00	130	0.00	130	0.00
Platform time	5h43.07	5h43.49		5h43.47		5h43.28		5h44.05		5h43.50	
# of extras	0	0		0		0		0		0	
Platform time	0h00	0h00		0h00		0h00		0h00		0h00	
Re. T. platform	743h27	744h57		744h54		744h11		745h32		745h00	
Sign-on/pull	160h06	155h14		153h29		155h09		155h49		154h34	
Join-up	4h48	0h08		0h18		0h18		0h00		0h00	
Paid meal	7h25	4h28		4h35		4h36		4h37		4h28	
Guaranteed run	11h35	21h14		11h06		15h19		14h00		19h24	
Overtime	8h38	2h48		4h07		1h37		2h53		3h06	
Spread rate 1	1h48	5h21		4h23		3h28		4h45		6h24	
Extra platform	0h00	0h00		0h00		0h00		0h00		0h00	
To. pay hour	937.38	934.17	-0.34	922.87	-1.55	924.63	-1.36	927.60	-1.04	932.93	-0.47

Unlike Cabot Garage, however Micro does generate satisfactory automated optimized crew schedules for Albany Garage (see *Table 4-14*). The required manpower (total runs, full-time duties and part-time duties) in most tests fit the constraints well. The corresponding platform times for full-time split and part-time duty types are very similar to the manual schedule. However no apparent relationships between the Macro results and their corresponding Micro schedules for Albany Garage were found (see *Figure 4-2*). No consistency was found between the Macro schedules and the corresponding Micro schedules for Albany, whether in terms of total pay hours, total runs, or number of part-time duties.

Figure 4-2: Comparison between Macro and Micro Schedules for Albany Garage

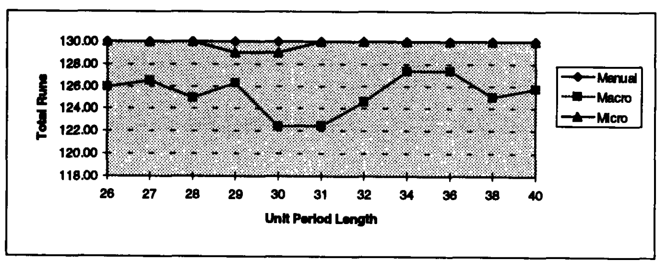
A. Total Pay Hours

Period	Macro	Micro
26	844.10	924.12
27	856.50	929.25
28	831.10	928.63
29	845.20	926.55
30	838.70	923.35
31	813.40	926.18
32	847.00	934.17
34	855.00	922.87
36	867.60	924.63
38	834.80	927.60
40	851.30	932.93



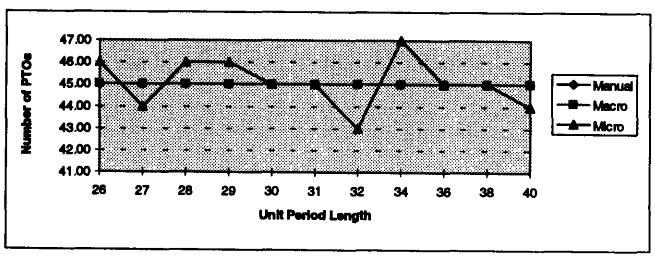
B. Total Runs

Period	Manual	Macro	Micro
26	130.00	125.94	130.00
27	130.00	126.53	130.00
28	130.00	124.93	130.00
29	130.00	126.26	129.00
30	130.00	122.43	129.00
31	130.00	122.50	130.00
32	130.00	124.62	130.00
34	130.00	127.33	130.00
36	130.00	127.36	130.00
38	130.00	125.00	130.00
40	130.00	125.72	130.00



C. Number of PTOs

Period	Manual	Macro	Micro
26	45.00	45.00	46.00
27	45.00	45.00	44.00
28	45.00	45.00	46.00
29	45.00	45.00	46.00
30	45.00	45.00	45.00
31	45.00	45.00	45.00
32	45.00	45.00	43.00
34	45.00	45.00	47.00
36	45.00	45.00	45.00
38	45.00	45.00	45.00
40	45.00	45.00	44.00



Virtually every Micro schedule in *Table 4-14* is an acceptable automated crew schedule which is quite different from the results for Cabot. The Micro schedule with the period length of 36 minutes is chosen as the base schedule in the following evaluation because of its comparatively low total pay hours and perfectly matched manpower (compared with the manual schedule). *Tests 1*, *3*, and *5* have lower total pay hours than *Test 9*. However, the number of part-time duties in *Tests 1* and *3* both exceed the upper limit (45), and *Test 5* has two extras in addition to the 129 regular runs.

4.3.3 Sensitivity Analysis

In *section 4.3.2*, some general Macro and Micro results for both garages were presented. We concluded that an acceptable Micro crew schedule could not be found for Cabot under current input file parameters. HASTUS created automated crew schedules which violate the manpower constraints (total runs and number of part-time duties) with unproductive duties having low platform times for split full-time and part-time duties. In contrast for Albany Garage, HASTUS produces acceptable automated crew schedules which perfectly match the manual schedule with even lower total pay hours. The results in *section 4.3.2.4* also show that there is little evidence of a relationship between the Macro schedules with different period lengths and their corresponding Micro schedules for both garages for current input files.

However almost all these results are based on very similar files and conditions. Since there are many possible conditions and parameter settings in the crew scheduling process (and available in HASTUS), a further analysis is necessary to test these conclusions. The first part of the evaluation in this section focuses on the impacts of different input files. The second part examines certain important parameters in the Macro file. The third part relaxes certain soft rules to seek an acceptable automated optimized schedule for Cabot.

4.3.3.1 Input Files

No acceptable automated crew schedule for Cabot Garage has yet been found. Since different PTO wage rates and different period lengths have been examined, the evaluation in this sub-section focuses on different input files to see if an acceptable automated crew schedule can be generated for Cabot Garage. Albany Garage will also be examined to see if further improvements can be obtained. Different input files are examined as shown in the table below with the results summarized in *Table 4-15*.

	Focus
Test 1	The parameter file: Different manpower constraints.
Test 2	The parameter file: Different minimum platform-time parameter.
Test 3	The parameter file: Different structure.
test 4	The Macro file: Different structure.
Test 5	Different combination of the parameter file and the Macro file.
Test 6	No selection file.
Test 7	No cutting file.

Test 1. The first test relaxed all the manpower constraints in the parameter files except for the part-time manpower constraint for both garages. The total-runs constraint is set as 0[42] and the maximum number of duties for all full-time duty types are relaxed to 999. This test is to examine what kind of Micro schedules HASTUS produces with virtually no full-time manpower constraints for both garages. The manpower constraint on part-time duties was not relaxed, since otherwise, a tremendous number of part-time duties would be generated because of the lower wage rate and the saving of premiums for part-time duties. For example, a total of 306 runs including 248 part-time duties were selected when the part-time manpower constraint was also relaxed in one experiment.

Compared with both the manual schedule and the base schedule, the test file did not result in any improvement for Cabot in terms of manpower and total pay hours as

[42] When the total-runs constraint is set as 0, it implies the number of runs suggested by Macro is to be generated [76].

shown in *Table 4-15*. The total runs and total pay hours in *Test 1* for Albany seem marginally better than the manual and base schedules, however, there are 2 extras with an average length of 4h40. This test would not necessarily be better after these extras are massaged into other duties. Therefore *Test 1* for both garages did not produce better results for either garage.

Table 4-15: Micro Schedules for Different Input Files

1. Cabot Garage

	manual	Base	(%)	Test 1	(%)	Test 2	(%)	Test 3	(%)	Test 4	(%)	Test 5	(%)	Test 6	(%)	Test 7	(%)
PTO wage rate	13.85	14		14		14		14		14		14		14		14	
Period length		27		27		27		27		27		27		27		27	
# of flo-str	28	17	-39.3	17	-39.3	16	-42.9	15	-46.4	23	-17.9	19	-32.1	15	-46.4	15	-46.4
2-piece	26	17		17		16		15		23		17		15		15	
3-piece	2											2					
Platform time	6h34	6h32		6h31		6h31		6h35		6h16		6h29		6h35		6h35	
# of flo-spl	154	171	11.0	145	-5.8	169	9.7	159	3.2	159	3.2	147	-4.5	172	11.7	173	12.3
2-piece	108	159		131		156		147		130		124		158		160	
3-piece	42	12		14		13		12		28		21		14		13	
4-piece	4									1		2					
Platform time	7h04	6h49		6h56		6h47		6h55		6h47		6h56		6h51		6h48	
# of pto	56	58	3.6	88	57.1	61	8.9	56	0.0	73	30.4	57	1.8	57	1.8	58	3.6
1-piece	2	16		56		17				38				12		17	
2-piece	54	41		31		41		53		35		55		43		40	
3-piece		1		1		3		3				2		2		1	
Platform time	4h56	4h46		4h45		4h52		4h57		4h29		4h54		4h51		4h43	
Total Runs	238	246	3.36	250	5.04	246	3.36	230	-3.36	255	7.14	223	-6.30	244	2.52	246	3.36
Platform time	6h30.58	6h19.13		6h08.58		6h18.10		6h25.24		6h05.03		6h23.01		6h22.11		6h18.10	
# of extras	0	0		5		1		16		0		29		0		1	
Platofrm time	0h00	0h00		4h22		3h39		5h08		0h00		4h48		0h00		5h52	
Re. T. platform	1550h53	1554h51		1537h25		1550h31		1477h25		1551h28		1423h36		1554h15		1550h32	
Sign-on/pull	186h06	189h30		177h57		190h16		185h04		193h23		179h06		187h46		181h05	
Join-up	11h30	3h12		2h23		3h33		3h11		8h15		8h24		3h24		3h02	
Paid meal	14h05	10h50		8h59		10h15		7h30		18h38		10h50		9h14		10h09	
Guaranteed run	3h12	38h57		17h03		37h51		20h44		30h33		14h03		34h25		45h36	
Overtime	32h55	14h47		14h29		10h20		17h25		12h35		17h29		15h17		10h46	
Spread rate 1	9h44	10h19		5h14		13h28		12h19		8h45		4h02		10h14		9h35	
Extra platform	0h	0h00		21h51		3h39		82h15		0h00		139h12		0h00		5h52	
To. pay hour	1808.42	1820.43	0.66	1785.35	-1.28	1819.88	0.63	1805.88	-0.14	1823.62	0.84	1796.70	-0.65	1814.58	0.34	1816.62	0.45

2. Albany Garage

	manual	Base	(%)	Test 1	(%)	Test 2	(%)	Test 3	(%)	Test 4	(%)	Test 5	(%)	Test 6	(%)	Test 7	(%)
PTO wage rate	13.85	16		16		16		16		16		16		16		16	
Period length		36		36		36		36		36		36		36		36	
# of flo-str	13	7	-46.2	5	-61.5	7	-46.2	6	-53.8	5	-61.5	6	-53.8	6	-53.8	10	-23.1
2-piece	13	7		5		7		6		5		6		6		10	
3-piece																	
Platform time	6h05	5h55		6h02		5h55		6h00		6h02		6h04		5h57		5h57	
# of flo-spl	72	78	8.3	76	5.6	78	8.3	79	9.7	80	11.1	79	9.7	77	6.9	68	-5.6
2-piece	57	77		76		78		77		60		62		77		68	
3-piece	14	1						2		20		17					
4-piece	1																
Platform time	6h30	6h31		6h36		6h30		6h31		6h28		6h30		6h32		6h41	
# of pto	45	45	0.0	46	2.2	45	0.0	45	0.0	45	0.0	45	0.0	47	4.4	48	6.7
1-piece																	
2-piece	44	45		46		45		45		44		44		47		48	
3-piece	1									1		1					
Platform time	4h21	4h19		4h27		4h19		4h17		4h18		4h16		4h21		4h25	
Total Runs	130	130	0.00	127	-2.31	130	0.00	130	0.00	130	0.00	130	0.00	130	0.00	126	-3.08
Platform time	5h43.07	5h43.28		5h48.09		5h43.32		5h43.51		5h42.45		5h42.55		5h43.36		5h45.56	
# of extras	0	0		2		0		0		0		0		0		6	
Platofrm time	0h00	0h00		4h40		0h00		0h00		0h00		0h00		0h00		4h01	
Re. T. platform	743h27	744h11		736h57		744h20		745h02		742h39		743h00		744h29		726h28	
Sign-on/pull	160h06	155h09		151h21		156h15		154h43		160h07		156h37		153h40		144h06	
Join-up	4h48	0h18		0h00		0h00		0h59		5h12		4h00		0h00		0h06	
Paid meal	7h25	4h36		2h39		4h11		3h21		3h04		3h30		3h25		6h51	
Guaranteed run	11h35	15h19		9h58		14h16		14h43		9h11		10h44		13h33		10h34	
Overtime	8h38	1h37		5h35		2h10		2h15		2h38		2h41		2h46		4h28	
Spread rate 1	1h48	3h28		5h58		6h00		5h38		4h21		4h56		5h14		4h11	
Extra platform	0h00	0h00		9h21		0h00		0h00		0h00		0h00		0h00		24h11	
To. pay hour	937.38	924.63	-1.36	921.82	-1.66	927.20	-1.09	926.68	-1.14	927.20	-1.09	925.47	-1.27	923.12	-1.52	920.92	-1.76

Test 2. The average platform times for full-time split duties and part-time duties in the automated crew schedules for Cabot are usually lower than in the manual schedule. This may explain why the automated crew schedule always needs more manpower than the manual schedule for Cabot Garage. This test increased the minimum-platform-time parameter for every duty type in the parameter files by 10 minutes for both garages to see if the platform times in the automated crew schedule would be increased. The same adjustments were also applied to Albany Garage to see if any improvement is possible.

The test files produced virtually identical Micro schedules to the base schedules for both garages. The increase of the minimum platform-time parameter seemed unable to produce any improvement for Cabot or Albany here.

Test 3. The third test is to see if different parameter files can improve the automated crew schedules for both garages. As shown in the Cabot Garage Micro schedules in previous sections (e.g. *Tables 4-8* and *4-12*), the number of required part-time operators in these Micro schedules usually results in the violation of the manpower constraints (total runs and part-time duties). In these Micro schedules, the number of 1-piece part-time duties are usually more than half the total required part-time duties. If these 1-piece part-time duties can be reduced, an acceptable Micro schedule which satisfies the manpower constraints may result for Cabot Garage. Since a 1-piece part-time duty type is included in the Albany base parameter file (*Appendix C7*), this duty type may be used to restrict the generation of 1-piece part-time duties (by setting the maximum allowed 1-piece part-time operators at 0 as in *Appendix C7*).

As a result, the parameter files originally used for both garages were exchanged in this test, i.e. the new parameter file for Cabot Garage was identical to the base Albany Garage parameter file except that the manpower parameters were set as before. The new parameter file for Albany Garage was identical to the base Cabot Garage parameter file with similar adjustments to the manpower parameters.

The number of 1-piece part-time operators for Cabot was expected to be reduced by setting a restriction on 1-piece part-time duties in this test. It seems that this restriction did prevent the generation of this kind of part-time duty type since there were no 1-piece part-time duties in these two Micro schedules is contrast with the other Cabot Garage Micro schedules. However, the significant number of trippers in these two schedules show this restriction resulted in HASTUS assigning these pieces of work as trippers instead of possible one-piece part-time duties.

Test 4. The fourth test is to examine the input of different types of Macro files. The Macro files originally used for both garages were exchanged, i.e. the new test Macro file for Cabot Garage was basically the same as the base Albany Garage Macro file with the max-number-drivers constraint relaxed from 45 to 56. The new test Macro file for Albany Garage was basically the same as the base Cabot Garage Macro file except for similar adjustments.

It seems that this new Macro file produced a worse schedule for Cabot Garage in terms of required part-time duties and total runs. For Albany Garage, this new Macro file did not make any significant improvement with a virtually unchanged Micro schedule resulting.

Test 5. The parameter files and the Macro files in this thesis were created by simulating the manual duties. The parameter file and the Macro file built for a specified garage are consistent with each other, especially in terms of duty types defined in both files. In *Tests 3* and *4*, only parameter files or Macro files were exchanged for each garage. The duty types defined in the test parameter file (Macro file) may not be consistent with the original Macro file (parameter file) for each garage. Therefore, the test parameter files in *Test 3* and the test Macro files in *Test 4* were used simultaneously in this test for each garage to examine if the matching input files could do any better than the previous two tests (also compared with the manual and base schedules).

As in *Test 3*, the number of 1-piece part-time operators for Cabot was expected to be reduced by setting a restriction on 1-piece part-time duties in the parameter file. This restriction did discourage the generation of this kind of part-time duty, however, even though a more consistent Macro file was employed for Cabot Garage, a significant number of trippers was still generated by HASTUS exactly as in *Test 3*. As in previous tests, almost unchanged micro schedules were generated for Albany Garage.

Tests 6 and 7. The base selection and cutting files used in the evaluation in this thesis are almost the minimum requirements[43] for the MBTA. Therefore, these two tests examine the potential impact a selection file or a cutting file may have on the final Micro schedule.

Without the selection file in *Test 6*, a resulting Micro schedule which is better than the Cabot Garage base schedule can be produced because of fewer restrictions. However, this does not prove that this is a feasible schedule, because some runs may be infeasible or unrealistic without the minimum requirements in the selection file. In general, without the restrictions of the selection file and the cutting file (*Test 7*), the generated Micro schedules for Cabot are better than other Micro schedules in *Table 4-11* in terms of required manpower (except for the base schedule with the period length of 27 minutes). In contrast, the relaxation of these two files made the Micro schedules for Albany worse because of more part-time duties.

It seems that these different input files still cannot help Micro find an acceptable schedule for Cabot, or even make significant improvements either for the Albany Garage automated crew schedule or for the base Cabot Garage schedule. The results from *Tests 1* to *5* show that neither different parameter files nor Macro files changed the final crew

[43] The platform-time parameters in the selection file for Cabot are not strictly necessary. They are added because the platform times of duties created in the automated crew schedule are usually lower than expected.

schedules significantly. For Albany Garage, most automated crew schedules generated are still acceptable as were those in the previous sections. Unfortunately, there is still no acceptable automated crew schedule for Cabot Garage in *Table 4-15*. There are several possible explanations for these results. First, the strict work rules of the MBTA increase the difficulty of both the manual and the automated crew scheduling tasks. In the general crew scheduling process, many small pieces of work will be left. It is not easy to form them into feasible duties, especially when trippers are not allowed and the number of part-time manpower is limited. In addition, the duty length constraint, the overtime constraint, and the premiums will also encourage HASTUS to use cheaper part-time duties. From the Cabot Garage schedules above, we can see that a large number of part-time duties or extras are inevitably produced.

There may be another reason to explain this situation. MBTA has a very challenging problem for both vehicle and crew scheduling. Instead of two peak demands, there are actually three peak demands in the MBTA. For Cabot Garage, there is another school-trip peak in addition to the two peaks shown in *Table 4-3*. This peak starts before the evening peak and overlaps with it. It requires 123 buses for the fall schedule of 1994. This extra long peak increases the difficulty in the assignment of buses and operators for both the manual scheduling and the automatic scheduling.

Another reason may result from inappropriate parameter settings in input files for the Cabot case. For example, the soft rule of the maximum allowed duty-length is used to be defined as 11h00 instead of 13h00 (legal length in the union contract) in the MBTA. This soft rule may prevent the generation of more FTOs instead of PTOs as expected in *Test 1*, or it may prevent the increase of FTO platform times as desired in *Test 2* which may decrease the required operators (either FTOs or PTOs). Another example is the fringe-benefits parameter in the macro file. In *Appendix C5*, the fringe-benefits parameters (35 and 30) for 2-piece split FTOs are lower than 3-piece split FTOs (45) and PTOs (75). In *Appendix C10*, this kind of parameter for both 2-piece or 3-piece split FTOs was defined as the same value (50), while a lower fringe-benefits parameter for PTOs (compared with that in *Appendix C5*) was set at 65. Since a new macro file as *Appendix C10* was used in both *Tests 4* and *5*, the comparatively lower fringe-benefits parameter (compared with original macro files as *Appendix C5* in other tests) for 3-piece split FTOs did help the generation of this kind of duties compared with the base schedule. The numbers of 2-piece split FTOs in both tests were also reduced because of the comparatively high fringe-benefit parameter. In addition, the comparatively low fringe-benefits parameter for PTOs also increased the number of required PTOs in *Test 4*. As for *Test 5, if* there was no restriction on the generation of 1-piece PTOs in the parameter file, 29 trippers generated might also be assigned as PTOs.

4.3.3.2 The Macro File

Many parameters can be used to approximate the union contract and other required criteria in Macro. The choice of suitable parameters and their corresponding values may be important for the final schedules (in Macro and Micro). The choice of certain parameters should be made carefully because of the characteristics (or limitations) of Macro and because of their possible impacts on the final schedules as well as their impacts on its use as a cost estimating procedure. The key question to be addressed in this section is how sensitive the final schedule is to the parameters selected.

1. Parameter Lengths: As mentioned above, the values defined in a Macro file must be consistent with the specified period length and approximate the key time attribute characteristics as closely as possible. Different selected values (parameter lengths) may greatly affect the Macro schedule and the corresponding Micro schedule. The prevention of trippers discussed in *section 4.3.2.4* (as well as in *Table 4-16*: *Base 2* and *Test 2-1*) shows exactly this kind of influence. However, the approximation of the key time attribute characteristics is usually limited by the available values associated with the specified period length, so some trade-offs have to be made in choosing a suitable parameter length.

Some examples with their impacts on the Macro schedules and Micro schedules are shown in *Tables 4-16* and *4-17* for Cabot and Albany respectively. *Base 1* and *Test 1-1* in *Table 4-16* show the first example of choosing a parameter length. As mentioned in *section 4.3.2.4*, 3-piece split full-time duties in the Cabot Macro file usually create too many variables for Macro to handle. The duty-length constraints (for split full-time duties) in the Macro file for *Test 1-1* perfectly match the actual work rule (8h05). However, these period lengths will fail in the Macro function since neither a Macro schedule nor a Micro schedule can be created. Therefore, the duty-length constraint for the 3-piece split full-time duty has to be lowered from 8h06 to 7h39 as in *Base 1* to help Macro work. This case shows that a closely matched value does not necessarily work well. If the duty-length constraints for both 2- piece and 3-piece split full-time duties are lowered to 7h39, the corresponding Macro and Micro schedules are slightly different from the base schedule (*Base 1*) in terms of manpower. Although required manpower (both total runs and the number of part-time duties) is slightly higher for *Test 1-2*, it does not prove that the parameter length which matches the criteria better is able to produce a better solution, at least this is not true for *Base 2* and its associated test schedules. *Test 2-2* which has the best matching parameter lengths created a Micro schedule with the highest required manpower (total runs and number of part-time duties) compared with *Base 2* and *Test 2-1*.

Base 2 and associated testing schedules also raise a different concern. The maximum full-time duty length at the MBTA is 8h05. In a Macro file with a period length of 34 minutes, it falls in the range between 7h56 and 8h30. It seems that 8h30 is too large to be the maximum duty length set in the Macro file for full-time duty types. However, it is possible for actual full-time duties to have duty lengths over 7h56. In such a case, the period length of 8h30 may to be a more appropriate constraint (parameter length) to allow this kind of duty. If many actual duties have lengths over 7h56 and the Macro maximum duty length of 7h56 is chosen, the corresponding Macro schedule or Micro schedule may not be able to produce more closely matching and/or more productive duties than the manual schedule (or the work rules). The trade-off between these two values which were used in the duty-length constraint for split full-time duties did have some impact on the Macro schedules and Micro schedules for Cabot Garage in terms of required manpower. However, there is still no positive correlation between Macro and Micro schedules for these period length trade-offs.

For *Base 1* and *Test 1-1*, when the duty-length constraints for split full-time duties were lowered, the total runs in both Macro and Micro schedules did increase because of lower duty lengths or slightly lower average platform times. However, for *Base 2* and *Test 2-1*, when the duty-length constraints for two 2-piece split full-time duties were lowered, its Macro schedule produced 20 trippers on top of almost the same required regular runs as *Base 2*. Moreover, this Macro file produces a Micro schedule as good as the best Micro schedule found (*Base 1*) so far.

Table 4-17 shows the corresponding results for Albany Garage. The only difference between these Macro files in *Table 4-17* is the duty-length constraint (the 46th constraint) of the split full-time duty type. This duty-length constraint is varied from 6h36 to 8h30 for three different period lengths. It turns out that these Macro files created virtually unchanged Macro or Micro schedules for Albany. The only differences between these schedules are the total runs and the number of split full-time duties in the Macro schedules. It seems that the selection of period lengths does not affect the final Macro and Micro schedules Albany Garage at all.

From these two tables, it seems that the selection of period length does not affect the Macro or Micro schedule for either garage significantly. The Micro schedules for Cabot are still as unacceptable as those created in the previous sections, and HASTUS can still produce acceptable Micro schedules for Albany no matter how period lengths are changed. In addition, no positive correlation was found between Macro schedules and Micro schedules for two garages even if different parameter lengths were used.

Table 4-16: Crew Schedules with Different Macro Parameter Lengths for Cabot

1. Macro Schedules

Macro base schedules: from Table 4-11

	Manual	*Base 1*	*Test 1-1*	*Test 1-2*	*Base 2*	*Test 2-1*	*Test 2-2*
PTO wage rate	*13.85*	*14*	*14*	*14*	*14*	*14*	*14*
Period length		*27*	*27*	*27*	*34*	*34*	*34*
Period selection		*(8h06, 7h39)*	*(8h06, 8h06)*	*(7h39, 7h39)*	*(8h30,7h22)*	*(7h56, 7h22)*	*(7h56, 7h56)*
# of fto-str	28	15	Too	15	15	15	15
# of fto-spl	154	158.54	Many	166.8	148.84	147.18	157.75
# of early		65.77	Variables	67.9	59.42	51.72	53
Duty length		8h06		7h39	8h30	7h56	7h56
Spread		10h15		9h46	10h08	9h24	8h55
# of 3-piece		39		36	43.16	36.36	46.75
Duty length		7h31		7h27	7h22	7h22	7h56
Spread		9h43		9h26	10h01	9h46	10h59
# of late		53.77		62.9	46.26	59.1	58
Duty length		8h06		7h39	8h30	7h56	7h56
Spread		9h07		8h34	9h28	8h41	8h41
# of pto	56	52.23		50.1	56	56	52.5
Duty length		5h51		5h51	6h14	6h14	6h14
Spread		12h33		12h29	12h42	12h37	12h47
Total Runs	238	225.77		231.9	219.84	218.18	225.25
Duty length		7h26		7h12	7h38	7h22	7h31
Spread		10h26		10h00	10h40	10h08	10h17
# of extras	0	0		0	0	20.45	0
Duty legth	0h00	0h00		0h00	0h00	3h38	0h00
Worked hrs		1561.9		1561.9	1563.4	1563.4	1563.4
hrs in extras		0		0	0	74.4	0
hrs in Guaranteed		9.3		43.7	23.7	20	0
hrs in overtime		12.8		0.9	31.7	1.8	2.6
hrs of paid break		1.8		1.4	0	0	0
hrs in spread		4.5		3.2	6.3	4.2	20.5
To. pay hour	1808.42	1590.30		1611.10	1612.43	1663.80	1586.50
# of pieces		461.00		469.00	453.00	464.00	467.00

2. Micro Schedules

Micro base schedules: from Table 4-12

	Manual	*Base 1*	*Test 1-1*	*Test 1-2*	*Base 2*	*Test 2-1*	*Test 2-2*
PTO wage rate	*13.85*	*14*	*14*	*14*	*14*	*14*	*14*
Period length		*27*	*27*	*27*	*34*	*34*	*34*
Period selection		*(8h06, 7h39)*	*(8h06, 8h06)*	*(7h39, 7h39)*	*(8h30,7h22)*	*(7h56, 7h22)*	*(7h56, 7h56)*
# of fto-str	28	17		15	16	15	15
2-piece	26	17		15	16	15	15
3-piece	2						
Platform time	6h34	6h32		6h35	6h31	6h35	6h35
# of fto-spl	154	171		172	170	174	168
2-piece	108	159		150	151	157	140
3-piece	42	12		22	19	17	28
4-piece	4						
Platform time	7h04	6h49		6h47	6h46	6h47	6h45
# of pto	56	58		61	64	57	68
1-piece	2	16		20	24	11	27
2-piece	54	41		41	40	46	41
3-piece		1					
Platform time	4h56	4h46		4h41	4h39	4h45	4h50
Total Runs	238	246		248	250	246	251
Platform time	6h30.58	6h19.13		6h15.53	6h12.39	6h18.32	6h11.04
# of extras	0	0		0	0	0	0
Platform time	0h00	0h00		0h00	0h00	0h00	0h00
Re. T. platform	1550h53	1554h51		1553h40	1552h46	1552h01	1552h20
Sign-on/pull	186h06	189h30		190h28	190h49	195h03	190h45
Join-up	11h30	3h12		3h54	3h39	3h09	5h26
Paid meal	14h05	10h50		8h42	11h02	8h52	8h40
Guaranteed run	3h12	36h57		37h13	39h32	37h32	36h03
Overtime	32h55	14h47		8h25	8h28	9h34	9h47
Spread rate 1	9h44	10h19		6h18	8h47	8h52	6h46
Extra platform	0h00	0h00		0h00	0h00	0h00	0h00
To. pay hour	1808.42	1820.43		1808.67	1815.05	1815.05	1809.78

Period selection: Selection of parameter periods in the macro file:
(the duty-length constraint for the 2-piece split fto duties,
the duty-length constraint for the 3-piece split fto duties)

Table 4-17: Crew Schedules with Different Parameter Lengths for Albany Garage

1. Macro Schedules

Macro base schedules: from Table 4-13

	Manual	Base 1	Test 1-1	Test 1-2	Base 2	Test 2-1	Base 3	Test 3-1	Test 3-2
PTO wage rate	16	16	16	16	16	16	16	16	16
Period length		36	36	36	31	31	34	34	34
Period selection		(6h36)	(7h48)	(8h24)	(7h14)	(6h43)	(6h48)	(7h56)	(8h30)
# of fto-str	13	5	5	5	5	5	5	5	5
2-piece	13		5	5	5	5	5	5	5
# of fto-spl	72	77.36	66.31	62.14	72.5	77.92	77.33	67.21	63.19
2-piece	57	77.36	58.31	43.14	69.5	76.92	75.33	52.21	41.38
3-piece	14		8	19	3	1	2	15	21.81
4-piece	1								
Duty length		6h36	7h44	8h13	7h13	6h43	6h47	7h48	8h18
Spread		9h11	9h45	10h08	9h28	9h14	9h17	9h56	10h10
# of pto	45	45	45	45	45	45	45	45	45
1-piece	44					1.92			
2-piece	1		45	45	45	43.08	45	45	45
Duty length		6h00	5h58	6h00	5h41	5h41	5h40	5h40	5h40
Spread		12h20	12h30	12h30	12h33	12h05	12h24	12h20	12h40
Total Runs	130	127.36	116.31	112.14	122.5	127.92	127.33	117.21	113.19
Duty length		6h23	7h01	7h17	6h38	6h20	6h22	6h57	7h12
Spread		10h21	10h52	11h08	10h39	10h17	10h26	10h54	11h12
# of extras	0	0	0	0	0	0	0	0	0
Worked hrs		780.6	780.6	780.6	778.6	778.6	779.7	779.7	779.7
hrs in extras		0	0	0	0	0	0	0	0
hrs in Guaranteed		87	2.2	0	32.1	71.5	74.2	0	0
hrs in overtime		0	0	17.6	0	0.5	0.1	3.4	21.1
hrs of paid break		0	4.8	11.4	2.6	0.5	1.1	8.5	12.4
hrs in spread		0	3.1	6.2	0.1	0	0	4.1	5.3
To. pay hour	937.38	867.60	789.67	815.80	813.37	851.10	855.07	798.70	809.70
# of pieces		246.00	233.00	234.00	237.00	245.00	247.00	240.00	239.00

2. Micro Schedules

Micro base schedules: from Table 4-14

	Manual	Base 1	Test 1-1	Test 1-2	Base 2	Test 2-1	Base 3	Test 3-1	Test 3-2
PTO wage rate	16	16	16	16	16	16	16	16	16
Period length		36	36	36	31	31	34	34	34
Period selection		(6h36)	(7h48)	(8h24)	(7h14)	(6h43)	(6h48)	(7h56)	(8h30)
# of fto-str	13	7	7	7	5	8	8	8	9
2-piece	13	7	7	7	5	8	8	8	9
Platform time	6h05	5h56	5h51	5h58	6h02	5h55	5h55	5h50	5h55
# of fto-spl	72	78	78	78	80	78	75	78	80
2-piece	57	77	77	74	78	77	74	78	78
3-piece	14	1	1	4	2	1	1		2
4-piece	1								
Platform time	6h30	6h31	6h29	6h29	6h31	6h30	6h35	6h33	6h28
# of pto	45	45	45	45	45	44	47	44	41
2-piece	44	45	45	45	45	44	47	44	41
3-piece	1								
Platform time	4h21	4h19	4h25	4h23	4h17	4h18	4h19	4h16	4h15
Total Runs	130	130	130	130	130	130	130	130	130
Platform time	5h43.07	5h43.28	5h44.09	5h44.02	5h44.01	5h43.47	5h43.47	5h44.12	5h44.07
# of extras	0	0	0	0	0	0	0	0	0
Re. T. platform	735h34	744h11	745h41	745h25	745h23	744h53	744h54	745h47	745h36
Sign-on/pull	155h30	155h09	155h20	157h41	155h04	155h29	153h29	152h17	155h50
Join-up	0h52	0h18	0h16	0h56	1h10	0h28	0h18	0h00	0h29
Paid meal	3h53	4h36	4h08	3h49	2h39	4h57	4h35	4h50	5h14
Guaranteed run	17h33	15h19	17h34	14h54	12h42	14h02	11h06	18h14	21h27
Overtime	3h49	1h37	3h33	2h13	3h04	2h07	4h07	8h19	5h59
Spread rate 1	4h54	3h28	5h47	5h38	6h09	4h58	4h23	6h46	6h44
Extra platform	10h41	0h00	0h00	0h00	0h00	0h00	0h00	0h00	0h00
To. pay hour	937.38	924.63	932.32	930.57	926.18	926.90	922.87	936.22	941.32

Period selection: Selection of parameter lengths in the macro file: (the duty-length constraint for the split fto duties)

Test 2-1 in *Table 4-16* is a very interesting and rare case for HASTUS. As shown in *Table 4-16*, even though the Macro schedule of *Test 2-1* has 20 trippers, the associated Micro schedule is as good as the best Micro schedule found for Cabot so far. In general, only one optimized Micro schedule is available for every Macro file (Micro schedule). However, the Micro schedule of *Test 2-1* is just the best schedule among several Micro schedules which can be produced by this Macro file. *Table 4-18* shows all possible Micro schedules created by this Macro schedule. The base Micro schedule in *Table 4-18* is the initial Micro schedule for this specified Macro schedule. When the optimization function was employed, choices are identified between *swing* or *pull* for two relief opportunities for String #1 of route #1 at 4:39 p.m. and 1:24 p.m.[44]. If two *swings* are selected for these two opportunities, the optimized schedule would be created as shown in *Test 1* in *Table 4-18*. However, if either of these two relief opportunities is chosen as *pull*, some error message will appear[45]. The Micro schedules then would be reported by HASTUS as *Test 2* and *Test 3* which contain many trippers.

Table 4-18: Special Micro Schedules for Cabot Garage

	manual	*Base*	(%)	*Test 1*	(%)	*Test 2*	(%)	*Test 2-1*	(%)	*Test 3*	(%)	*Test 3-1*	(%)
Optimization		*Before*		*After*		*After*		*After*		*After*		*After*	
PTO wage rate	*13.85*	*14*		*14*		*14*		*14*		*14*		*14*	
Period length		*34*		*34*		*34*		*34*		*34*		*34*	
Period selection		*(7h56, 7h22)*		*(7h56, 7h22)*		*(7h56, 7h22)*		*(7h56, 7h22)*		*(7h56, 7h22)*		*(7h56, 7h22)*	
Swing selection				*(swing, swing)*		*(pull,)*				*(swing, pull)*			
# of flo-str	28	15	-46.4	16	-42.9	16	-42.9	16	-42.9	16	-42.9	15	-46.4
2-piece	26	15		16		16		16		16		15	
3-piece	2												
Platform time	6h34	6h35		6h34		6h34		6h34		6h34		6h35	
# of flo-spl	154	105	-31.8	170	10.4	62	-59.7	172	11.7	141	-8.4	174	13.0
2-piece	108	83		147		54		164		124		157	
3-piece	42	22		23		8		8		17		17	
4-piece	4												
Platform time	7h04	7h03		6h48		6h54		6h47		6h49		6h47	
# of pto	56	133	138	60	7.1	20	-64.3	56	0	50	-10.7	57	2
1-piece	2	56		17				1		14		11	
2-piece	54	76		43		5		55		36		46	
3-piece		1				15							
Platform time	4h56	4h47		4h48		4h51		4h50		4h47		4h45	
Total Runs	238	253	6.3	246	3.4	98	-58.8	244	2.5	207	-13.0	246	3.4
Platform time	6h30.58	5h50.18		6h18.33		6h25.46		6h19.56		6h19.07		6h18.32	
# of extras	0	26		0		297		1		81		0	
Platform time	0h00	3h18		0h00		3h29		7h30		3h24		0h00	
Re. T. platform	1550h53	1477h07		1552h05		630h04		1548h08		1307h59		1552h01	
sign-on/pull	186h06	179h18		192h42		74h20		197h06		160h21		195h03	
join-up	11h30	4h47		4h47		0h54		0h54		3h09		3h09	
paid meal	14h05	7h30		9h38		8h22		8h39		9h38		8h52	
Guaranteed run	3h12	12h12		31h24		11h25		39h39		26h03		37h32	
Overtime	32h55	19h31		11h05		6h37		10h35		9h58		9h34	
Spread rate 1	9h44	11h37		7h07		3h06		8h49		6h11		8h52	
Extra platform	0h00	86h00		0h00		1037h24		7h30		276h14		0h00	
To. pay hour	1808.42	1798.03	-0.57	1808.80	0.02	1772.20	-2.00	1819.30	0.60	1809.26	0.05	1815.05	0.37

Swing selection: Two relief opportunities as shown below will be identified to choose between a swing (swing) or a set of pull-in & pull-out (pull).
(1) The relief-type on String #1 (Route #1) at Dudly Square at 4:39 p.m.
(2) The relief-type on String #1 (Route #1) at Dudly Square at 1:42 p.m.
* Test 2-1 and Test 3-1 are the optimized micro schedules based on Test 2 and Test 3 respectively, not based on the base schedule.

However, if the optimization function is re-employed on these two schedules (*Test 2* and *Test 3*), the re-optimized schedules would be as shown for *Test 2-1* and *Test 3-1* respectively. *Test 2-1* has the lowest total runs yet created in an automated crew schedule for Cabot, and the only one tripper prevents this Micro schedule from becoming the best

44 This kind of situation is very rare. In general, HASTUS will decide relief types for every case by itself during the automated crew scheduling process.

45 The message is shown as: "Pull pieces have been used. The assignment file does not agree with this selection."

Micro schedule found so far for Cabot. This tripper is a long piece of work which starts at about 9:00 a.m. and ends at 4:39 p.m.. This long piece of work violates the maximum piece-length constraint (6h00) in the MBTA union contract.

2. Fringe-benefits Parameter: In our experience, the *fringe-benefits* parameter in Macro that can be added to every duty type may be very helpful to direct the final schedules. For example, in addition to narrowing the permissible ranges of some constraints for the 3-piece duty type, we can also put a higher fringe-benefit penalty on it than on other 2-piece duty types for Cabot Garage. This can help Macro as well as the corresponding Micro to produce more 2-piece duties as shown in *Table 4-19.* The base Macro file in *Table 4-19* is identical to the Macro file in *Appendix C5*. The only difference between the base Macro file and the first test Macro file (*Test 1*) is that the fringe-benefits parameter (the 58th parameter) for the 3-piece duty type was reduced from 45 to 35 in the testing file. The Macro and Micro schedules are virtually the same for *Base* and *Test 1.* Nevertheless, the manpower requirements in both Macro and Micro schedules have changed. The lower fringe benefit encourages HASTUS to produce more 3-piece duties in both Macro and Micro schedules (for the first testing Macro file). Compared with the base schedule, this change also reduced the number of part-time duties and the total pay hours in the Micro schedule.

However, the use of the *fringe-benefits* parameter does not always guarantee reaching the desired objectives. Since the number of part-time duties could be reduced by lowering the *fringe-benefits* parameter for 3-piece duties, the second test file (*Test 2*) increased the *fringe-benefits* parameter for the 2-piece part-time duty type (the 86th constraint in *Appendix C5*) from 75 to 150 to discourage the employment of part-time duties in both Macro and Micro schedules. The fringe-benefits parameter of 1-piece part-time duties (the 95th constraint) was also increased from 100 to 999 to prevent the generation of trippers. The resulting Macro and Micro schedules (*Test 2* in *Table 4-19*) are basically the same as the base schedules. The number of part-time operators does not decrease in either Macro or Micro schedules as desired.

Table 4-19: Crew Schedules with Different Fringe Benefits for Cabot Garage

1. Macro Schedules

	Base	Test 1	Test 2
PTO wage rate	14	14	14
Period length	31	31	31
Fringe benefits	(45, 75, 100)	(35, 75, 100)	(45, 150, 999)
# of flo-str	15	15	15
# of flo-spl	156.46	161.01	160
# of early	55	28.83	49.5
Duty length	8h16	8h16	8h16
Spread	9h17	9h09	9h17
# of 3-piece	36.77	79.85	40
Duty length	6h59	7h11	6h49
Spread	9h26	9h26	9h15
# of late	64.69	52.33	70.5
Duty length	8h16	8h16	8h16
Spread	9h05	9h02	9h04
# of pto	59.27	56.53	57
Duty length	5h41	5h41	5h41
Spread	12h21	12h28	12h28
Total Runs	229.73	231.54	231
Duty length	7h20	7h12	7h19
Spread	10h05	10h06	10h03
# of extras	0	0	0
Worked hrs	1561.9	1561.9	1561.9
hrs in extras	0	0	0
hrs in Guaranteed	18.2	52	20.1
hrs in overtime	25	15.8	22.7
hrs of paid break	9	3.6	10.1
hrs in spread	0	0	0
To. pay hour	1614.10	1633.30	1614.80
# of pieces	466	515.00	472.00

2. Micro Schedules

	Manual	Base	Test 1	Test 2
PTO wage rate	13.85	14	14	14
Period length		31	31	31
Fringe benefits		(45, 75, 100)	(35, 75, 100)	(45, 150, 999)
# of flo-str	28	17	15	15
2-piece	26	17	15	15
3-piece	2			
Platform time	6h34	6h29	6h35	6h35
# of flo-spl	154	166	171	168
2-piece	108	142	110	143
3-piece	42	24	57	25
4-piece	4		4	
A. platform time	7h04	6h45	6h45	6h42
# of pto	56	68	62	69
1-piece	2	28	20	31
2-piece	54	39	38	38
3-piece		1	4	
Platform time	4h56	4h36	4h44	4h30
Total Runs	238	248	247	251
Platform time	6h30.58	6h09.43	6h14.21	6h05.39
# of extras	0	1	0	3
Platform time	0h00	5h56	0h00	5h56
Re. T. platform	1550h53	1546h40	1547h20	1535h47
Sign-on/pull	186h06	192h34	194h49	192h17
Join-up	11h30	5h32	12h33	4h38
Paid meal	14h05	10h39	10h50	9h51
Guaranteed run	3h12	37h39	33h59	44h59
Overtime	32h55	9h26	13h29	7h16
Spread rate 1	9h44	5h10	7h14	5h59
Extra platform	0h00	5h56	0h00	17h50
To. pay hour	1808.42	1813.60	1820.23	1818.62

Macro base schedule: from Table 4-11
Micro base schedule: from Table 4-12
Fringe benefits: Fringe benefits defined in the macro file for key duty types: (3-piece flo duty, 2-piece pto duty, tripper)

Table 4-20 shows the corresponding cases for Albany Garage. The test Macro files are basically the same as the base Macro file (see *Appendix C10*). Because the split full-time duty type is preferred for a final schedule, the first test (*Test 1*) lowered the fringe-benefits parameter (the 56th parameter) of the split full-time duty type from 50 to 30. The second test (*Test 2*) increased the fringe-benefits parameter (the 70th parameter) of the part-time duty type from 65 to 130 to discourage the generation of part-time duties. The first test did increase the number of split full-time duties slightly by decreasing the number of part-time duties in Macro and Micro schedules, however, the number of part-time duties increased in the Micro schedules of the second test.

Through these tests, the fringe-benefits parameter seems unable to affect the final Micro schedules (the total pay hours, required manpower) significantly in both Macro and Micro schedules for both garages. In addition, as with the results for different period lengths, different fringe benefits cannot help create an acceptable Micro schedule for Cabot or improve the Micro schedule significantly for Albany.

Table 4-20: Crew Schedules with Different Fringe Benefits for Albany Garage

1. Macro Schedules

	Base	Test 1	Test 2
PTO wage rate	16	16	16
Period length	34	34	34
Fringe benefits	(50, 65)	(30, 65)	(50, 130)
# of fto-str	**5**	**5**	**5**
# of fto-spl	**77.33**	**81**	**81**
2-piece	75.33	75	75
3-piece	2	6	6
Duty length	6h47	6h45	6h45
Spread	9h15	9h35	9h22
# of pto	**45**	**41**	**41**
2-piece	45	41	41
Duty length	5h40	5h40	5h40
Spread	12h11	12h21	12h20
Total Runs	**127.33**	**127**	**127**
Duty length	6h22	6h23	6h23
Spread	10h20	10h27	10h22
# of extras	0	0	0
Worked hrs	779.7	779.7	779.7
hrs in extras	0	0	0
hrs in Guaranteed	74.2	78.6	78.6
hrs in overtime	0.1	0.1	0.1
hrs of paid break	1.1	3.4	3.4
hrs in spread	0	0	0
To. pay hour	**855.1**	**861.8**	**861.8**
# of pieces	247.00	250.00	250.00

Macro base schedules: from Table 4-13
Micro base schedules: from Table 4-14

Fringe benefits: Fringe benefits defined in the macro file for key duty types: (split fto duty (regular late fto), pto duty)

2. Micro Schedules

	Manual	Base	Test 1	Test 2
PTO wage rate	13.85	16	16	16
Period length		34	34	34
Fringe benefits		(50, 65)	(30, 65)	(50, 130)
# of fto-str	**13**	**8**	**8**	**6**
2-piece	13	8	8	6
Platform time	**6h05**	5h55	6h02	6h00
# of fto-spl	**72**	**75**	**79**	**77**
2-piece	57	74	76	74
3-piece	14	1	3	3
4-piece	1			
Platform time	**6h30**	6h35	6h27	6h27
# of pto	**45**	**47**	**43**	**46**
1-piece				
2-piece	44	47	43	46
3-piece	1			
Platform time	**4h21**	4h19	4h19	4h24
Total Runs	**130**	**130**	**130**	**129**
Platform time	**5h43.07**	5h43.47	5h43.49	5h42.07
# of extras	**0**	**0**	**0**	**2**
Platform time	**0h00**	0h00	0h00	5h20
Re. T. platform	**743h27**	744h54	744h57	735h34
Sign-on/pull	**160h06**	153h29	155h52	155h30
Join-up	**4h48**	0h18	0h46	0h52
Paid meal	**7h25**	4h35	4h22	3h53
Guaranteed run	**11h35**	11h06	18h04	17h33
Overtime	**8h38**	4h07	3h01	3h49
Spread rate 1	**1h48**	4h23	6h25	4h54
Extra platform	**0h00**	0h00	0h00	10h41
To. pay hour	**937.38**	**922.87**	**933.45**	**932.77**

3. The Wage-Rate Parameter in the Macro file: As shown in *Appendixes C5* and *C10*, only one global wage rate is used in the Macro files for all duties as is the habit in the MBTA, i.e. the wage rates for full-time or part-time duties are set as the same value (set in the global *hourly-rate* parameter) in the Macro file. This may affect the way Macro cuts the blocks or matches duties. However, there should be no significant impact on the final Micro schedule from this kind of option, because the parameter file which has defined separated wage rates for full-time and part-time duty types should have greater (final) influence in forming the Micro schedule. To prove this, we re-conduct the most important parts of the evaluation (the impact of different PTO rates in *section 4.3.2.2* and the impact of different period lengths in *section 4.3.2.4*) with separate wage rates for full-time duties and part-time duties in the Macro file for both garages. Except for this difference, all the files or parameters are the same as in the previous two sections.

Table 4-21: Micro Schedules for Different PTO Wage Rates and Macro PTO Rates

1. Cabot — **Micro base schedules:** from Table 4-8

	manual	*Base 1*	*Test 1-1*	*Base 2*	*Test 2-1*	*Base 3*	*Test 3-1*	*Base 4*	*Test 4-1*
PTO wage rate	*13.85*	*10*	*10*	*20*	*20*	*30*	*30*	*100*	*100*
Period length		*31*	*31*	*31*	*31*	*31*	*31*	*31*	*31*
Macro wage rate		*(18.46,18.46)*	*(18.46,10)*	*(18.46,18.46)*	*(18.46,20)*	*(18.46,18.46)*	*(18.46,30)*	*(18.46,18.46)*	*(18.46,100)*
# of flo-str	28	15	16	17	16	18	18	16	15
2-piece	26	15	16	17	16	18	18	16	15
3-piece	2								
Platofim time	6h34	6h35	6h32	6h29	6h34	6h27	6h33	6h32	6h35
# of flo-spl	154	167	168	169	169	164	167	168	167
2-piece	108	140	151	143	137	136	135	140	129
3-piece	42	27	17	26	32	28	32	28	36
4-piece	4								2
Platform time	7h04	6h44	6h47	6h43	6h40	6h50	6h45	6h47	6h42
# of pto	56	71	65	69	68	70	67	70	68
1-piece	2	32	22	34	33	30	31	34	24
2-piece	54	39	43	35	34	40	36	36	40
3-piece					1				4
Platform time	4h56	4h33	4h42	4h26	4h27	4h24	4h27	4h17	4h50
Total Runs	238	253	249	255	253	252	252	254	250
Platform time	6h30.58	6h06.43	6h14.07	6h05.14	6h04.05	6h08.05	6h07.59	6h05.09	6h11.28
# of extras	0	1	0	0	3	1	1	1	0
Platform time	0h00	5h56	0h00	0h00	5h56	5h56	5h56	5h56	0h00
Re. T. platform	1550h53	1546h23	1552h39	1552h15	1535h16	1545h58	1545h34	1545h51	1547h48
sign-on/pull	186h06	191h58	191h59	192h05	189h35	193h29	193h46	192h39	198h30
join-up	11h30	4h19	3h14	5h12	7h16	4h44	5h00	6h29	11h07
paid meal	14h05	8h51	9h57	11h24	8h43	10h56	10h15	11h09	10h05
Guaranteed run	3h12	43h58	37h21	47h38	54h23	31h12	44h04	39h12	39h56
Overtime	32h55	7h44	10h30	8h47	8h56	17h06	17h24	18h35	13h07
Spread rate 1	9h44	5h31	6h53	5h40	6h36	6h15	6h22	9h04	7h16
Extra platform	0h00	5h56	0h00	0h00	17h50	5h56	5h56	5h56	0h00
To. pay hour	1808.42	1814.67	1820.67	1823.02	1828.58	1815.60	1828.35	1828.92	1827.82

2. Albany — **Micro base schedules:** from Table 4-9

	manual	*Base 1*	*Test 1-1*	*Base 2*	*Test 2-1*	*Base 3*	*Test 3-1*	*Base 4*	*Test 4-1*
PTO wage rate	*13.85*	*10*	*10*	*20*	*20*	*30*	*30*	*100*	*100*
Period length		*34*	*34*	*34*	*34*	*34*	*34*	*34*	*34*
Macro wage rate		*(18.46,18.46)*	*(18.46,10)*	*(18.46,18.46)*	*(18.46,20)*	*(18.46,18.46)*	*(18.46,30)*	*(18.46,18.46)*	*(18.46,100)*
# of flo-str	13	7	7	7	8	8	8	6	8
2-piece	13	7	7	7	8	8	7	6	8
3-piece							1		
Platofim time	6h05	6h04	6h03	6h00	6h03	5h57	5h55	6h00	6h01
# of flo-spl	72	78	79	78	77	79	79	81	76
2-piece	57	77	78	77	76	78	77	79	72
3-piece	14	1	1	1	1	1	2	2	4
4-piece	1								
Platofim time	6h30	6h27	6h26	6h30	6h30	6h31	6h30	6h33	6h29
# of pto	45	45	44	45	45	43	43	43	44
1-piece									
2-piece	44	45	44	45	45	43	43	43	44
3-piece	1								
Platofim time	4h21	4h24	4h24	4h20	4h20	4h14	4h16	4h08	4h23
Total Runs	130	130	130	130	130	130	130	130	128
Platofim time	5h43.07	5h43.59	5h44.0	5h44.08	5h43.57	5h44.11	5h44.01	5h44.12	5h44.35
# of extras	0	0	0	0	0	0	0	0	4
Platofim time	0h00	0h00	0h00	0h00	0h00	0h00	0h00	0h00	2h48
Re. T. platform	743h27	745h18	745h22	745h39	745h15	745h45	745h23	745h46	735h08
sign-on/pull	160h06	154h46	156h28	154h40	156h53	154h48	154h35	154h45	155h10
join-up	4h48	0h15	0h15	0h15	0h15	0h15	0h42	0h31	1h21
paid meal	7h25	3h59	4h02	3h33	4h37	4h23	5h07	3h25	4h29
Guaranteed run	11h35	16h16	16h39	14h23	14h15	16h48	18h47	15h57	15h36
Overtime	8h38	1h53	1h24	3h53	5h09	7h18	6h07	10h05	9h18
Spread rate 1	1h48	4h51	4h54	4h23	4h11	6h09	4h55	9h39	5h31
Extra platform	0h00	0h00	0h00	0h00	0h00	0h00	0h00	0h00	11h13
To. pay hour	937.38	927.3	929.07	926.77	930.58	935.4	935.6	940.13	937.77

Macro wage rate: Wage rates defined in the macro file: (full-time duty types, part-time duty type)

Table 4-21 reevaluates the impact of different PTO wage rates on final Micro schedules (especially for the number of part-time duties) which was presented in *section 4.3.2.2*. The base schedules for both garages are the same as the test results in *Tables 4-8* and *4-9* (*section 4.3.2.2*). The PTO wage rate in the Macro file is now varied along with the PTO wage rate defined in the parameter file. As shown in *Table 4-21* for both garages, the number of part-time duties in every resulting schedule was slightly reduced, but the results are similar to the base schedules. The Micro schedules with the PTO wage rates of as high as $30 or $100 still do not reduce the number of part-time duties significantly. As concluded in *section 4.3.2.2*, even though the PTO wage rates in the Macro file are varied along with the PTO wage rates in the parameter file, this parameter is still unable to influence the number of part-time duties for either garage. In addition, there is no significant improvement for Micro schedules for both garages along with this kind of adjustment.

4.3.3.3 Relaxed FTO Spread-length Constraints

As mentioned in *section 4.2.2*, the maximum spread-length constraint is always set as 11 hours for all full-time duties as a soft rule for any crew scheduling process (manual or automated) in the MBTA. This soft rule may greatly restrict the ability of HASTUS to provide an acceptable optimized Micro schedule for Cabot Garage. If longer spread full-time runs are allowed, the number of part-time duties and total runs may be reduced to satisfy the manpower constraints in Cabot Garage as desired by the MBTA. This kind of restriction may also lead to the Cabot Garage results noted in *sections 4.3.2.2* and *4.3.3.1*. In *section 4.3.2.2*, even if the PTO wage rate is as high as $30 or even $100, the number of PTO duties for the Cabot schedules remained constant at about 70 (*Table 4-8*). When the PTO wage rate is $100, HASTUS would choose not to produce any part-time duties and instead assign a significant number of trippers. The test schedules (*Tests 3* and 5) in *Table 4-15* in *section 4.3.3.1* show a similar result. When the one-piece part-time duties which usually amount to half the total part-time duties were restricted by a specific duty type (as both *pto1 duty type* in *Appendix C10*), HASTUS would assign these pieces of work as trippers instead. It seems that this kind of maximum FTO spread-length soft rule may make PTOs and trippers the only option for the tests in these two sections (maybe in other sections, too). Since the maximum FTO duty length defined in the MBTA union contract is 13 hours, in this section we re-evaluate the impact of this soft rule by relaxing it. Since the current soft rule can usually help HASTUS create acceptable Micro schedules for Albany Garage, the evaluation in this section will focus on Cabot Garage.

Appendix D presents the new parameter file, the new selection file, and the new Macro file for the evaluation in this section with the relaxation of the maximum FTO spread length from 11h00 to 13h00. All the maximum FTO spread-length constraints are relaxed in both the parameter file and the Macro file. As for the new selection file, the platform-time constraints and the constraint with the high penalty to prevent the generation of straight full-time duties were eliminated, because more straight duties may be generated from the relaxation of this soft rule and help create an acceptable Micro schedule for Cabot Garage. The elimination of platform-time constraints is also to relax as many restrictions as possible which might have reduced the ability of HASTUS to develop a good schedule for Cabot Garage. The initial assignment file and the cutting file are as before.

Table 4-22 shows the results of a similar evaluation as shown in *section 4.3.2.2* for Cabot Garage: the impact of different PTO wage rates on Micro schedules. The base schedules are exactly the same as in *Table 4-8* in *section 4.3.2.2*. The test schedules result from the new input files (with the relaxation of the maximum duty-length constraint). Compared with the base schedules, the number of PTOs and total runs have been reduced to close to those obtained in the manual schedule. This is accompanied by a significant decrease in the number of one-piece part-time duties. The number of one-piece PTOs has been reduced by about 20 in all test schedules as desired by assigning these pieces of work to FTOs thus increasing the FTO average platform times. The relaxation of the maximum spread-length constraint also helped increase the number of 3-piece FTOs (except in *Test 5*) and the average platform time of total runs. In addition, the make-up time-costs were virtually eliminated. However, the overtime penalties and spread premiums were greatly increased, especially the spread premiums over 11 hrs (*Spread rate premium = 2*).

Table 4-22: Micro Schedules with Different PTO Wage Rates for Cabot Garage

1. Base Schedules

	manual	Base 1	(%)	Base 2	(%)	Base 3	(%)	Base 4	(%)	Base 5	(%)
PTO wage rate	13.85	10		13.85		20		28		30	
Max spread		11h22		11h22		11h22		11h22		11h22	
Period length		31		31		31		31		31	
# of flo-str	28	15	-46.4	16	-42.9	17	-39.3	16	-42.9	18	-35.7
2-piece	26	15		16		17		16		18	
3-piece	2										
Platform time	6h34	6h35		6h32		6h29		6h31		6h27	
# of flo-spl	154	167	8.4	166	7.8	169	9.7	167	8.4	164	6.5
2-piece	108	140		139		143		140		136	
3-piece	42	27		27		26		27		28	
4-piece	4										
Platform time	7h04	6h44		6h42		6h43		6h49		6h50	
# of pto	56	71	26.8	73	30.4	69	23.2	70	25.0	70	25.0
1-piece	2	32		36		34		30		30	
2-piece	54	39		37		35		39		40	
3-piece								1			
Platform time	4h56	4h33		4h29		4h26		4h24		4h24	
Total Runs	238	253	6.30	255	7.14	255	7.14	253	6.30	252	5.88
Platform time	6h30.58	6h06.43		6h03.48		6h05.14		6h08.01		6h08.05	
# of extras	0	1		1		0		0		1	
Platform time	0h00	5h56		5h56		0h00		0h00		5h56	
Re. T. platform	1550h53	1546h23		1546h10		1552h15		1551h49		1545h58	
sign-on/pull	186h06	191h58		192h03		192h05		193h17		193h29	
join-up	11h30	4h19		5h14		5h12		5h35		4h44	
paid meal	14h05	8h51		11h10		11h24		10h40		10h56	
Guaranteed run	3h12	43h58		44h56		47h38		32h31		31h12	
Overtime	32h55	7h44		7h28		8h47		16h08		17h06	
Spread rate 1	9h44	5h31		5h24		5h40		5h39		6h15	
Extra platform	0h00	5h56		5h56		0h00		0h00		5h56	
To. pay hour	1808.42	1814.67	0.35	1818.35	0.55	1823.02	0.81	1815.65	0.40	1815.60	0.40

2. Test Schedules

	manual	Test 1	(%)	Test 2	(%)	Test 3	(%)	Test 4	(%)	Test 5	(%)
PTO wage rate	13.85	10		13.85		20		28		30	
Max spread		13h02		13h02		13h02		13h02		13h02	
Period length		34		34		34		34		34	
# of flo-str	28	18	-35.7	17	-39.3	16	-42.9	18	-35.7	21	-25.0
2-piece	26	17		16		16		18		21	
3-piece	2	1		1							
Platform time	6h34	6h34		6h31		6h37		6h31		6h29	
# of flo-spl	154	167	8.4	172	11.7	169	9.7	170	10.4	166	7.8
2-piece	108	124		121		124		127		140	
3-piece	42	43		51		45		42		25	
4-piece	4							1		1	
Platform time	7h04	6h53		6h53		6h56		6h52		6h56	
# of pto	56	56	0.0	56	0.0	58	3.6	54	-3.6	55	-1.8
1-piece	2	8		16		12		16		15	
2-piece	54	48		40		45		38		40	
3-piece						1					
Platform time	4h56	4h45		4h22		4h32		4h38		4h26	
Total Runs	238	241	1.26	245	2.94	243	2.10	242	1.68	242	1.68
Platform time	6h30.58	6h22.26		6h17.33		6h21.11		6h20.33		6h20.05	
# of extras	0	2		2		1		8		7	
Platform time	0h00	5h56		3h46		5h56		2h12		2h54	
Re. T. platform	1550h53	1536h09		1541h42		1543h50		1534h54		1533h02	
sign-on/pull	186h06	203h05		201h26		196h03		201h09		195h35	
join-up	11h30	18h59		20h41		16h19		13h07		11h18	
paid meal	14h05	18h24		18h07		16h19		26h35		28h19	
Guaranteed run	3h12	0h05		0h05		0h05		0h05		0h05	
Overtime	32h55	29h27		27h24		29h35		26h06		30h04	
Spread rate 1	9h44	28h24		29h11		25h46		29h38		28h50	
Spread rate 2	0h00	30h49		28h00		27h48		29h47		34h21	
Extra platform	0h00	11h53		7h33		5h56		17h39		20h19	
To. pay hour	1808.42	1876.43	3.76	1874.15	3.63	1860.85	2.90	1878.35	3.87	1881.88	4.06

Max spread: The max-spread constraint for dull-time duty types.

It is not surprising that the total pay hours were also increased because of the allowed longer spreads. It seems that the relaxation of the maximum spread-length constraint can produce better Micro schedules in terms of the required work force (total runs and number of part-time duties) although at a significant cost in terms of total pay hours.

However, the results also confirm that different PTO wage rates still do not have great influence on the number of part-time duties generated. As the PTO wage rates is varied from 10 to 30, the number of part-time duties in the final Micro schedules remains constant at about 56 (excluding trippers).

To further explore the impact of the relaxation of the maximum spread-length constraint, another evaluation is presented regarding the impact of different period lengths on Macro and Micro schedules as in *section 4.3.2.4*. The base schedules in *Tables 4-23* and *4-24* are identical to the schedules in *Tables 4-11* and 4-12 in *section 4.3.2.4*. *Tables 4-23* and *4-24* also present the Macro and Micro schedules for the new input files and different period lengths. The fringe-benefits parameter of 3-piece FTOs in the Macro file with period length of 27 minutes is slightly different from other schedules because of the previously mentioned limitation of the Macro function (maximum 2900 variables). Not until other parameters (e.g. the range-start parameter, the mealbreak-length parameter, the piece-length parameter, and the duty-length parameter) are tightened[46] and the *fringe-benefits* parameter increased from 45 to 55 does this Macro file work.

Except for *Test 1*, other Macro schedules (*Tests 2, 3-1, 4-1*[47]) are quite different from the base schedules in terms of split FTOs. It seems that the maximum spread length of 13h00 helped Macro produce more 3-piece split FTOs instead of early 2-piece FTOs. However, the average spread lengths for different duty types do not necessarily increase

[46] For example, the duty-length constraint for 3-piece FTOs was reduced from 8h06 to 7h39. The maximum piece-length parameter was reduced from 5h51 to 3h36.

[47] *Tests 3-2* and *3-3* will be discussed later.

(e.g. the average duty lengths of 3-piece and late 2-piece FTOs in *Base 3* and *Test 3-1*) because of the relaxation of maximum allowed spread length.

Table 4-23: Macro Schedules with Different Period Lengths for Cabot Garage

	manual	Base 1	(%)	Test 1	(%)	Base 2	(%)	Test 2	(%)	Base 3	(%)
PTO wage rate	13.85	14		14		14		14		14	
Max spread		11h22		13h02		11h22		13h02		11h22	
Fringe benefit		45		55		45		45		45	
Period length		27		27		29		29		31	
# of flo-str	28	15	-46.4	15	-46.4	15	-46.4	15	-46.4	15	-46.4
Platform time	6h34										
# of flo-spl	154	158.54	2.9	164	6.5	162	5.2	164	6.5	156.46	1.6
Platform time	7h04										
# of early		65.77		61		54		6		55	
Duty length		8h06		8h06		8h13		8h13		8h16	
Spread		10h15		9h43		9h33		10h02		9h17	
# of 3-piece		39		29		30		86		36.77	
Duty length		7h31		6h17		6h42		7h03		6h59	
Spread		9h43		8h39		8h55		9h18		9h26	
# of late		53.77		74		78		72		64.69	
Duty length		8h06		8h06		8h13		8h13		8h16	
Spread		9h07		8h55		9h01		9h03		9h05	
# of pto	56	52.23	-6.7	56	0.0	56	0.0	56	0.0	59.27	5.8
Platform time	4h56										
Duty length		5h51		5h51		6h17		6h17		5h41	
Spread		12h33		12h04		12h32		12h32		12h21	
Total Runs	238	225.77	-5.14	235	-1.26	233	-2.10	235	-1.26	230.73	-3.05
Platform time	6h30.58										
Duty length		7h26		7h17		7h31		7h16		7h20	
Spread		10h26		9h54		10h02		10h02		10h05	
# of extras	0	0		0		0		0		0	
Worked hrs		1561.9		1561.9		1561.7		1561.7		1561.9	
hrs in extras		0		0		0		0		0	
hrs in Guaranted		9.3		5.3		11.8		8.6		18.2	
hrs in overtime		12.8		20.1		20.1		17.8		25	
hrs of paid break		1.8		28.4		10.2		49.3		9	
hrs in spread		4.5		0		0		0		0	
To. pay hour	1808.42	1590.30	-12.1	1615.70	-10.7	1603.80	-11.3	1637.40	-9.5	1614.10	-10.7
# of pieces		461.00		469.00		467.00		526.00		466.00	

	manual	Test 3-1	(%)	Test 3-2	(%)	Base 4	(%)	Test 4-1	(%)	Test 4-2	(%)
PTO wage rate	13.85	14		14		14		14		14	
Max spread		13h02		13h02		11h22		13h02		13h02	
Fringe benefit		45		55		45		45		55	
Period length		31		31		34		34		34	
# of flo-str	28	15	-46.4	15	-46.4	15	-46.4	15	-46.4	15	-46.4
Platform time	6h34										
# of flo-spl	154	163	5.8	163	5.8	148.84	-3.4	162	5.2	162	5.2
Platform time	7h04										
# of early		20		58		59.42		6		51.5	
Duty length		8h16		8h16		8h30		8h30		8h30	
Spread		9h27		9h36		10h08		9h30		9h25	
# of 3-piece		80		29		43.16		106		30	
Duty length		7h01		6h21		7h22		7h01		7h00	
Spread		9h20		8h44		10h01		9h21		9h15	
# of late		63		76		46.26		50		80.5	
Duty length		8h16		8h16		8h30		8h30		8h30	
Spread		8h57		9h03		9h28		9h21		9h20	
# of pto	56	56	0.0	56	0.0	56	0.0	56	0.0	56	0.0
Platform time	4h56										
Duty length		6h12		6h12		6h14		6h14		6h14	
Spread		12h15		12h18		12h42		12h48		12h37	
Total Runs	238	234	-1.68	234	-1.68	219.84	-7.63	233	-2.10	233	-2.10
Platform time	6h30.58										
Duty length		7h17		7h29		7h38		7h12		7h43	
Spread		9h59		9h59		10h40		10h14		10h11	
# of extras	0	0		2		0		0		0	
Worked hrs		1561.9		1561.9		1563.4		1563.4		1563.4	
hrs in extras		4.1		4.1		0		0		0	
hrs in Guaranted		6.7		2.4		23.7		47.6		9.6	
hrs in overtime		19.4		33.3		31.7		18.9		44.6	
hrs of paid break		33.6		29.5		0		26.2		10.7	
hrs in spread		0		0		6.3		0		0	
To. pay hour	1808.42	1625.70	-10.1	1631.20	-9.8	1625.10	-10.1	1656.10	-8.4	1628.30	-10.0
# of pieces		520.00		470.00		453.00		543.00		464.00	

Fringe benefit: The value of the fringe-benefit parameter for the 3-piece split full-time duty type in the macro file.

These Macro schedules are virtually unchanged for different period lengths in terms of total runs, average platform times, and total pay hours. The total pay hours in test Macro schedules are all slightly greater than the base schedules because of more overtime penalties and paid breaks[48].

Table 4-24: Micro Schedules with Different Period Lengths for Cabot Garage

	manual	Base 1	(%)	Test 1	(%)	Base 2	(%)	Test 2	(%)	Base 3	(%)
PTO wage rate	13.85	14		14		14		14		14	
Max spread		11h22		13h02		11h22		13h02		11h22	
Fringe benefit		45		55		45		45		45	
Period length		27		27		29		29		31	
# of flo-str	28	17	-39.3	20	-28.6	17		17	-39.3	17	-39.3
2-piece	26	17		20		17		17		17	
3-piece	2										
Platform time	6h34	6h32		6h24		6h29		6h29		6h28	
# of flo-spl	154	171	11.0	166	7.8	168		168	9.1	166	7.8
2-piece	108	159		150		145		123		142	
3-piece	42	12		16		23		44		24	
4-piece	4							1			
Platform time	7h04	6h49		7h02		6h41		6h56		6h46	
# of pto	56	58	3.6	54	-3.6	68		56	0.0	68	21.4
1-piece	2	16		5		32		6		28	
2-piece	54	41		49		36		48		39	
3-piece		1						2		1	
Platform time	4h56	4h46		4h42		4h30				4h36	
Total Runs	238	246	3.36	240	0.84	253		241	1.26	251	5.46
Platform time	6h30.58	6h19.13		6h27.49		6h05.34		6h25.12		6h09.43	
# of extras	0	0		0		2		0		1	
Platform time	0h00	0h00		0h00		5h56		0h00		5h56	
Re. T. platform	1550h53	1554h51		1551h16		1541h31		1547h16		1546h40	
Sign-on/pull	186h06	189h30		193h12		191h45		199h56		192h34	
Join-up	11h30	3h12		7h35		4h45		14h53		5h32	
Paid meal	14h05	10h50		21h15		11h33		18h44		10h39	
Guaranteed run	3h12	36h57		0h05		48h49		0h05		37h39	
Overtime	32h55	14h47		33h08		8h12		31h00		9h26	
Spread rate 1	9h44	10h19		33h10		8h55		26h04		5h10	
Spread rate 2		0h00		37h43		0h00		25h14		0h00	
Extra platform	0h	0h00		0h00		11h53		0h00		5h56	
To. pay hour	1808.42	1820.43	0.66	1877.40	3.81	1827.38		1863.20	3.03	1813.60	0.29

	manual	Test 3-1	(%)	Test 3-2	(%)	Base 4	(%)	Test 4-1	(%)	Test 4-2	(%)
PTO wage rate	13.85	14		14		14		14		14	
Max spread		13h02		13h02		11h22		13h02		13h02	
Fringe benefit		45		55		45		45		55	
Period length		31		31		34		34		34	
# of flo-str	28	20	-28.6	20	-28.6	16	-42.9	20	-28.6	16	-42.9
2-piece	26	20		20		16		20		16	
3-piece	2										
Platform time	6h34	6h27		6h23		6h31		6h24		6h32	
# of flo-spl	154	171	11.0	168	9.1	170	10.4	167	8.4	165	7.1
2-piece	108	137		146		151		132		147	
3-piece	42	34		21		19		35		18	
4-piece	4			1							
Platform time	7h04	6h58		6h58		6h46		6h57		6h59	
# of pto	56	47	-16.1	55	-1.8	64	14.3	54	-3.6	62	10.7
1-piece	2	8		13		24		11		13	
2-piece	54	38		42		40		43		49	
3-piece		1									
Platform time	4h56	4h38		4h31		4h39		4h36		4h32	
Total Runs	238	238	0.00	243	2.10	250	5.04	241	1.26	243	2.10
Platform time	6h30.58	6h28.16		6h22.26		6h12.39		6h22.54		6h20.01	
# of extras	0	8		3		0		5		2	
Platform time	0h00	1h51		1h36		0h00		2h29		5h56	
Re. T. platform	1550h53	1540h11		1548h54		1552h46		1538h00		1539h05	
Sign-on/pull	186h06	192h14		190h24		190h49		198h40		199h58	
Join-up	11h30	13h03		7h44		3h39		11h26		6h30	
Paid meal	14h05	24h06		30h41		11h02		21h55		19h45	
Guaranteed run	3h12	0h05		0h05		39h32		0h05		0h05	
Overtime	32h55	35h42		30h15		8h28		27h31		29h41	
Spread rate 1	9h44	32h38		31h13		8h47		29h33		30h03	
Spread rate 2	0h00	41h03		37h20		0h00		28h38		31h56	
Extra platform	0h00	14h51		4h50		0h00		12h25		11h53	
To. pay hour	1808.42	1893.88	4.73	1881.43	4.04	1815.05	0.37	1868.22	3.31	1868.93	3.35

48 This may result from the generation of more 3-piece FTOs.

As show in *Table 4-24*, the test Micro schedules are much better than the base schedules in terms of required operators with lower numbers of PTOs and total runs required. The number of 3-piece FTOs also increased. An acceptable Micro schedule (*Test 1*) which is very close to the manual schedule was finally found for Cabot Garage. This Micro schedule even had lower required PTOs as desired by the MBTA. However there is still no apparent correlation between Macro and Micro schedules in terms of total pay hours. For example, the Macro schedules of *Tests 2* and *3* are very similar, but their corresponding Micro schedules are quite different in terms of PTOs and trippers.

Compared with the Macro schedules of *Test 1* and other tests, the distribution of split FTOs is quite different resulting from different fringe-benefits parameters. Since the Macro schedule of *Test 1* could help generate an acceptable Micro schedule for Cabot Garage, it is interesting to examine if this Micro result can be derived from similar Macro schedules as *Test 1*. Accordingly, the fringe-benefits parameters in *Tests 3-2* and *4-2* were increased to 55 as in *Test 1*. The resulting Macro schedules for *Tests 3-2* and *4-2* were really close to *Test 1*. However, these Macro schedules were not able to produce similar acceptable Micro schedules as *Test 1*. This also again showed the lack of correlation between these Macro and Micro schedules. One interesting result affects the 3-piece FTOs. Compared with *Tests 3-1* and *4-1*, fewer 3-piece FTOs were generated in *Tests 3-1* and *4-1*. It seems that the fringe-benefits parameter in the Macro schedule could indeed affect the generation of 3-piece FTOs in the Micro schedule. However, as concluded in *section 4.3.3.2*, it still had no great influence on the final Micro schedule in terms of manpower (total runs, total split FTOs, or total pay hours, etc.). The make-up (*Guaranteed run*) time-costs in all test Micro schedules equal 5 minutes, because the duty lengths for all full-time duties except one fixed straight full-time duty (with the duty length of 7h45) are greater or equal to 7h50. It seemed that HASTUS tended to reduce make-up costs and increase spread premiums with the help of the relaxation of the FTO spread-length constraint.

It seems that HASTUS is indeed able to provide an acceptable automated crew schedule for Cabot Garage which is quite different from the conclusion in previous sections. However, the Micro schedule of *Test 1* in *Table 4-24* seemed quite unique. Other Macro schedule with very similar conditions (parameters, input files, etc.) were not able to produce this kind of acceptable Micro schedule for Cabot Garage. This may imply that, unlike Albany Garage, the Cabot Garage case is very sensitive to parameter settings in input files. In addition, the total pay hours was significantly higher for the Cabot Garage automated crew schedule than the manual one (by about 3%) and there was considerable reliance on spreads over 11 hours, which are not required in the manual solution.

4.3.4 Analysis of Different Work Rules

In previous sections, no clear correlations existed between Macro schedules and the corresponding Micro schedules for both Cabot Garage and Albany Garage as parameters and other inputs were varied. However, the variation between these Macro and Micro schedules is not great because they are all based on very similar conditions. To further examine the potential of Macro solution to predict final Micro schedule cost, it may be better to examine more radical changes in work rules. Since the Cabot Garage schedules are very sensitive to parameter settings, it may be hard to tell whether changes in Macro or Micro schedules result from the changes in work rules or other parameters in the Cabot case. Thus the evaluation in this section will focus only on the Albany case. The Macro and Micro schedules with a period length of 36 minutes, which were generated in *Tables 4-13* and *4-14* and is the best feasible Micro schedule found so far for Albany, was chosen as the base Macro and Micro schedules. Their associated input files were used as the base input files. Three different major changes in work rules are examined in this section.

Scenario 1. Trippers are allowed.

All the restrictions on trippers in the macro file, such as the 14th constraint to 18th constraint in *Appendix C10*, were eliminated. The maximum number of extras in the parameter file (the extra-number parameter in *Appendix C7-1*) was relaxed from 0 to 999. The extra-penalty parameter was set at 0 instead of 10 and the extra-rate parameter was set as 1 instead of 1.5 in the parameter file. In addition, the high penalty to prevent the generation of straight FTOs in the selection file (the 4th constraint in *Appendix C8*) was totally relieved here (also in the following two tests).

Table 4-25 shows the resulting Macro and Micro schedules. The Macro schedules in the test (*Test 1*) were exactly the same as in the base case. Even before the use of the *optimization* function, no tripper was generated in the initial Micro schedule of *Test 1*[49], not to mention the optimized Micro schedule (*Test 1* in *Table 4-25*). It seemed that HASTUS could perfectly cut and match the Albany Garage vehicle schedule according to the input files without having to generate any tripper, even though there was no restriction preventing the generation of trippers. The elimination of the great penalty on straight FTOs in the selection file did help the initial Micro schedule of *Test 1* generate more straight FTOs (13) than the base schedule. However, when the *optimization* function was applied in *Test 1*, the number of straight FTOs was reduced to 7 as in the base schedule, while the number of PTOs will be reduced to 43 and the number of split FTOs will be increased to 80.

It seemed that there was no significant influence from this change on either the Macro or Micro schedules. The resulting Macro and Micro schedules are basically the same as the base Macro and Micro schedules.

Scenario 2. A new split FTO duty type with the maximum allowed duty length relaxed from 7h50 to 9h50 was built, i.e. there were two split FTO duty types in this test:

[49] This is also obvious while comparing with all the base schedules, which are all initial micro schedules, in *Table 4-7*.

one had the 8 hours' guaranteed pay (7h50 plus 10-minute sign-on allowance), and the other had the 10 hours' guaranteed pay (9h50 plus 10-minute sign-on allowance). The spread premiums for all FTOs were relaxed: FTO spreads over 12 hours are paid 1.5 times the regular wage rate. The maximum spread lengths for all FTOs were relaxed from 11h00 to the legal limit of 13h00.

Table 4-25: Crew Schedules with Different Work Rules for Albany Garage

1. Macro Schedules

Macro base schedules: from Table 4-13

		Manual		Base		(%)	Test 1		(%)	Test 2		(%)	Test 3		(%)
PTO wage rate		13.85		16			16			16			16		
Period length				36			36			36			36		
Scenario				Original			Tripper allowed			Longer duty			Longer overtime		
# of fto-str		13		5		-61.5	5		-61.5	5		-61.5	5		-61.5
# of fto-spl		72		77.36		7.4	77.36		7.4	62.07		-13.8	58.5		-18.8
	2-piece				77.36			77.36			44.07			32	
	3-piece										18			26.5	
Duty length				6h36			6h36			8h14			8h44		
Spread				9h11			9h11			10h23			10h29		
# of pto		45		45		0.0	45		0.0	45		0.0	45		0.0
	1-piece				0.36			0.36			3				
	2-piece				44.64			44.64			42			45	
Duty length				6h00			6h00			6h00			6h00		
Spread				12h20			12h20			11h58			12h45		
Total Runs		130		127.36		-2.0	127.36		-2.0	112.07		-13.8	108.5		-16.5
Duty length				6h23			6h23			7h17			7h33		
Spread				10h21			10h21			11h09			11h28		
# of extras		0		0			0			0			0		
Worked hrs				780.6			780.6			780.6			780.6		
hrs in extras				0			0			0			0		
hrs in Guaranteed				87			87			0			0		
hrs in overtime				0			0			17.6			34.1		
hrs of paid break				0			0			10.8			15.9		
hrs in spread				0			0			0			8.3		
To. pay hour		937.38		867.6		-7.4	867.6		-7.4	809		-13.7	838.9		-10.5
# of pieces				246.00			246.00			232.00			235.00		

2. Micro Schedules

Micro base schedules: from Table 4-14

		Manual		Base		(%)	Test 1		(%)	Test 2		(%)	Test 3		(%)
PTO wage rate		13.85		16			16			16			16		
Period length				36			36			36			36		
Scenario				Original			Tripper allowed			Longer duty			Longer overtime		
# of fto-str		13		7		-46.2	7		-46.2	6		-53.8	9		-30.8
	2-piece		13		7			7			6			8	
	3-piece													1	
Platform time		6h05		5h55			5h55			6h07			5h57		
# of fto-spl		72		78		8.3	80		11.1	80		11.1	79		9.7
	2-piece		57		77			80			76			74	
	3-piece		14		1						4			5	
	4-piece		1												
Platform time		6h30		6h31			6h27			6h31			6h28		
# of pto		45		45		0.0	43		-4.4	44		-2.2	42		-6.7
	1-piece														
	2-piece		44		45			43			44			42	
	3-piece		1												
Platform time		4h21		4h19			4h20			4h15			4h17		
Total Runs		130		130		0.0	130		0.0	130		0.0	130		0.0
Platform time		5h43.07		5h43.28			5h43.43			5h44.06			5h44.12		
# of extras		0		0			0			0			0		
Platform time		0h00		0h00			0h00			0h00			0h00		
Re. T. platform		743h27		744h11			744h44			745h34			745h46		
Sign-on/pull		160h06		153h29			154h24			159h58			160h46		
Join-up		4h48		0h18			0h00			1h16			2h00		
Paid meal		7h25		4h36			4h27			3h33			5h14		
Guaranteed run		11h35		15h19			21h44			6h57			14h12		
Overtime		8h38		1h37			2h36			1h56			5h18		
Spread rate 1		1h48		3h28			5h26			0h00			8h23		
Spread rate 2		0h00		0h00			0h00			0h00			2h15		
Extra platform		0h00		0h00			0h00			0h00			0h00		
To. pay hour		937.38		924.63		-1.4	933.35		-0.4	919.23		-1.9	943.90		0.7

Original: Current MBTA work rules.
Tripper allowed: Trippers are allowed in the micro schedule.
Longer duty: The maximum duty length is relaxed from 7h50 to 10h00.
Longer overtime: The maximum overtime length is relaxed from 15 mins to 1 hr.

Accordingly, the spread length constraints, the spread-rate parameters in the parameter file and the macro file for all FTOs were changed. The duty-length constraint in the parameter and macro files for the new split FTO duty type was set as 9h50. In addition, the overtime constraints for this new FTO type were also relaxed from 7h50 to 9h50 (in both parameter and Macro files), and the maximum allowed platform-time constraint as well as the maximum paid-time constraint (similar to the duty-length constraint in the macro file) in the parameter file were also modified from 8h05 to 10h05 (including 15-minute allowed overtime).

Compared with the base schedule, these relaxation significantly reduced the make-up time-costs and resulted in lower total pay hours in the Macro schedule (*Test 2*). The average spreads for split FTOs were also increased. As a result, total required runs was reduced.

However, these changes seemed to have little influence on the resulting Micro schedule which was virtually the same Micro schedule as the base schedule. No split FTO duty with the 10 hours' guaranteed pay was assigned. It seemed that split FTO duties with the 10 hours' guaranteed pay were not economical enough to be employed. To prove this, we changed the fringe-benefits parameter of this kind of split FTO duty type (from 50 to 20), almost all split FTOs in the resulting Macro schedule had 10 hours' guaranteed pay, but the resulting Micro schedule was still the same as *Test 2* or the base Micro schedule.

Scenario 3. The maximum overtime was relaxed from 15 minutes to 1 hour.

The maximum paid-time parameters for all FTOs in the parameter file were relaxed from 8h05 to 8h50, as were the duty-length constraints for all FTOs in the macro file. In addition, all the spread-length parameters for FTOs were relaxed from 11h00 to 13h00.

As in *Test 2*, the average spread for split FTOs in the Macro file was increased compared with the base schedule. And the total required runs was reduced. This improvement also helped reduce the make-up time-costs and thus reduced the total pay hours in the test Macro file.

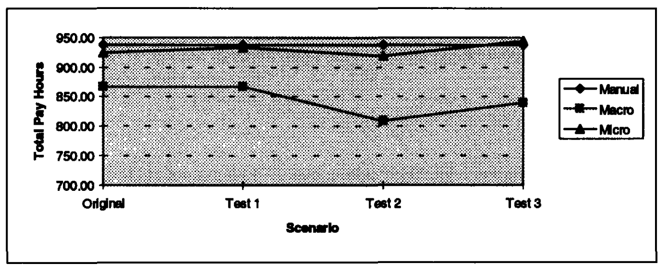
Compared with the base Micro schedule, the test Micro schedule (*Test 3*) produced more FTOs and reduced required PTOs. However, there was still no significant impact shown in this Micro schedule.

Figure 4-3 shows the relationship between the test Macro schedules and Micro schedules. It seemed that no significant positive correlation existed between these Macro schedules and Micro schedules. It was not obvious that Macro would be able to reflect the potential impact of significant changes on the final crew schedule for current parameter settings in these cases.

Figure 4-3: Comparison between Macro and Micro Schedules for Albany Garage

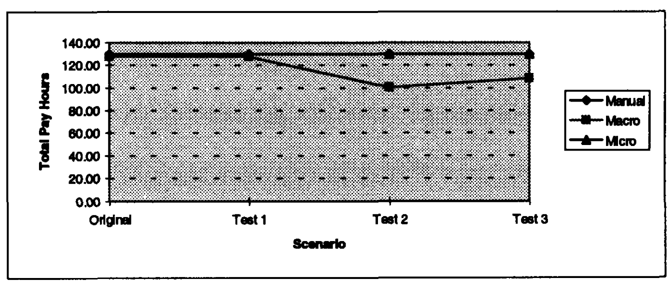
A. Total Pay Hours

Scenario	Manual	Macro	Micro
Original	937.38	867.60	924.63
Test 1	937.38	867.60	933.35
Test 2	937.38	809.00	919.23
Test 3	937.38	838.90	943.90



B. Total Runs

Scenario	Manual	Macro	Micro
Original	130.00	127.36	130.00
Test 1	130.00	127.36	130.00
Test 2	130.00	100.39	130.00
Test 3	130.00	108.50	130.00



4.4 Conclusions

In *section 4.3.2.1*, it seemed that HASTUS tended to create more part-time duties and trippers in an initial Micro solution than the number allowed in the parameter file (the hard rules). However, the *optimization* function available in Micro was able to delete many trippers after the initial Micro solution was generated. Under the current hard rules and soft rules in the MBTA, this function worked well for Albany Garage. It could delete all trippers and reduce the number of part-time duties to a satisfactory level for an initial Albany Garage Micro solution. For Cabot Garage, however it could not guarantee to delete all trippers, nor could it meet the maximum allowed part-time duties constraint desired by the MBTA, resulting in an unacceptable automated crew schedule. This function would usually increase total pay hours compared with the initial Micro schedule for both garages.

In *sections 4.3.2.2* and *4.3.2.3*, different PTO wage rates (varied from $10 per hour to $100 per hour) and different PTO manpower constraints had little effect on the number of PTOs with virtually unchanged optimized Micro schedules resulting for both garages. At no PTO wage rate was HASTUS able to create an acceptable optimized Micro schedule for Cabot Garage under current hard and soft rules. In contrast, HASTUS could usually create an acceptable optimized Micro schedule perfectly matching the manpower requirements for Albany Garage.

In *section 4.3.2.4*, acceptable Macro schedules resulted for both garages at different period lengths. Required total runs in Macro were all lower than the manual schedules for both garages, and required PTOs in both Cabot Garage or Albany Garage Macro schedules perfectly matched the manpower constraints. Optimized Micro schedules produced for Albany Garage were almost identical to their corresponding Macro schedules matching the manual schedule. However, optimized Micro schedules for Cabot Garage resulting from different period lengths were quite different from their corresponding Macro schedules, specially in terms of required total runs and required PTOs. Different period lengths produced basically unchanged Macro and optimized Micro schedules for both garages. No significant correlation was found between the Macro schedules and the corresponding optimized Micro schedules for both garages under base parameter settings. Any Macro schedules had much lower total pay hours than corresponding optimized Micro schedules as well as the manual schedules for both garages, because total pay hours in any Macro schedules exclude sign-on allowances, pull-in and pull-out costs, and join-up costs.

In *section 4.3.3.1*, different input files still were unable to produce an acceptable optimized Micro schedule for Cabot Garage under current hard and soft rules and they also produced virtually unchanged optimized Micro schedules for Albany Garage. In *section 4.3.3.2*, different parameter lengths in the Macro files did create slightly different Macro schedules for both garages, however corresponding optimized Micro schedules were basically unchanged. Different fringe-benefits parameters in the Macro files also resulted in basically unchanged optimized Micro schedules for both garages. In addition, it seemed that the use of a global wage rate file or the use of different wage rates for FTOs and PTOs in the Macro file did not significantly affect the results presented in *sections 4.3.2.2* and *4.3.2.4* under current hard and soft rules: different PTO wage rates still could not be used to control the number of required PTOs.

In *section 4.3.3.3*, the relaxed FTO spread-length rule (from 11 hours to the legal limit of 13 hours) for Cabot Garage resulted in Micro schedules which were quite different from those created in previous tests. Manpower requirements (total runs and PTOs) in these Micro schedules were much closer to the desired level. An acceptable optimized Micro schedule which matched the manpower requirements (total runs and part-time duties) was also found. In addition, this relaxation helped HASTUS prevent the generation of any full-time duty (except for fixed FTOs) with a duty length less than 7h50. The relaxation of the FTO spread length constraint above did not guarantee the result of an acceptable optimized Micro schedule for Cabot Garage. Other appropriate parameter settings, such as a suitable period length, were also very important. The evaluation also showed that this relaxation usually resulted in greater total pay hours in a Cabot Garage optimized Micro schedule, by about 3% over the manual schedule.

In *section 4.3.4*, radically different work rules showed little impact on Albany Garage Macro and Micro schedules. The first test showed that HASTUS would not generate any trippers for the Albany Garage Macro or Micro schedules, even if all restrictions against trippers were eliminated. In addition, the Micro schedules resulting from these changes were virtually unchanged and no significant positive correlation was found between these Macro and Micro schedules. It was not obvious that Macro could reflect the impact resulting from different changes, although it was not possible to examine a wide range of Micro inputs to see if actual crew schedules better approximating the Macro results could be obtained.

From the evaluations above, it seemed that Cabot Garage optimized Micro schedules were quite sensitive to certain parameter settings but insensitive to others. Only with very careful parameter settings could HASTUS create an acceptable automated crew schedule for Cabot Garage. In contrast, an acceptable and satisfactory automated crew schedule which had lower total pay hours and satisfactory required work force characteristics could readily be found for Albany Garage.

Chapter 5: Summary and Conclusions

This chapter briefly summarizes this thesis and suggests topics for further research based on the findings of this thesis.

5.1 Thesis summary

The first part of the thesis explored the general problem of vehicle and crew scheduling. The roles of scheduling in both the transportation planning process and the operational planning process were discussed. The formulations and models for vehicle scheduling and crew scheduling are presented separately. We also discuss and summarize key elements in the formulation of vehicle and crew scheduling problems. The differences of scheduling problems between the urban public transportation systems and the airlines are also briefly described. At the end, approaches to joint vehicle and crew scheduling problem are presented compared with the traditional sequential scheduling process.

The evolution of the computer-based scheduling system is discussed in the second part. The earliest computer-based scheduling systems were not flexible enough to be used easily and effectively across different authorities with varied constraints and requirements. Therefore, the concept of *the interactive environment* was introduced in the development of computer-based scheduling system for urban public transportation. This function enables schedulers to get more involved in the computer-based scheduling process. The newer generation of systems are designed to allow schedulers more control over the final schedule, and thus make the computer system flexible to be readily usable across many different authorities. Several computer systems and general heuristic methodologies are introduced in this part.

The final part presents the impacts of the installation and the results of the evaluations of HASTUS in the MBTA context. The installation of HASTUS had resulted in several impacts already. First, the size of the scheduling staff has been reduced substantially from around 10 to 6 at the current time, while the scheduler productivity has increased substantially. In the MBTA, 42 schedules in fall 1994 were generated with the help of HASTUS compared with 20 schedules before in essentially the same production cycle. Second, the resulting schedules are more accurate because of the reduction in manually produced paperwork. With HASTUS, the computer system can help avoid errors, such as misplacement of pieces of work, using a piece twice in different duties, or calculation errors (travel time, piece-length, duty-length, or cost), during the scheduling process. Because of this increase in scheduling efficiency, HASTUS has also enabled schedulers to try different scenarios (for cutting blocks or combining pieces into runs) to produce more economical schedules. Third, the computer system can now provide more useful information (reports) faster not only for the Plans and Schedules Department, but also for other MBTA departments.

HASTUS has been installed at the MBTA since 1986. While the vehicle scheduling and interactive (manual) crew scheduling functions are now used routinely, the automatic crew scheduling function has not yet been fully used in the regular scheduling process at the MBTA. Therefore, the evaluation in this thesis focused on the potential additional benefits to the MBTA from automated crew scheduling.

There are several key differences between depots selected for the evaluation: Cabot Garage and Albany Garage. First, the fleet size and required operators (FTOs and PTOs) in Cabot Garage are almost twice that than in Albany Garage. Second, no street reliefs are allowed in Albany Garage while there is no such restriction for Cabot Garage. Third, the final Albany operator duty ends before 9:00 p.m., while the final Cabot operator duty ends between 1:00 a.m. and 2:00 a.m.. Finally, part-time duties in Albany Garage are a greater percentage of total runs than in Cabot Garage.

The evaluations showed that HASTUS tended to create more part-time duties and trippers in an initial Micro solution than the number allowed in the parameter file (the hard rules). However, the *optimization* function available in Micro was able to delete many trippers after the initial Micro solution was generated. Under the current hard rules and soft rules in the MBTA, this function worked well for Albany Garage. It deleted all trippers and reduced the number of part-time duties to a satisfactory level for an initial Albany Garage Micro solution. For Cabot Garage, however it could not guarantee to delete all trippers, nor could it meet the maximum allowed part-time duties constraint desired by the MBTA, resulting in an unacceptable automated crew schedule. This function would usually increase total pay hours compared with the initial Micro schedule for both garages.

Different PTO wage rates (varied from \$10 per hour to \$100 per hour) and different PTO manpower constraints had little effect on the number of PTOs with virtually unchanged optimized Micro schedules resulting for both garages. At no PTO wage rate was HASTUS able to create an acceptable optimized Micro schedule for Cabot Garage under current hard and soft rules. In contrast, HASTUS could usually create an acceptable optimized Micro schedule perfectly matching the manpower requirements for Albany Garage.

Acceptable Macro schedules resulted for both garages at different period lengths. Required total runs in Macro schedules were all lower than the manual schedules for both garages, and required PTOs in both Cabot Garage or Albany Garage Macro schedules perfectly matched the manpower constraints. Optimized Micro schedules produced for Albany Garage were almost identical to their corresponding Macro schedules matching the manual schedule. However, optimized Micro schedules for Cabot Garage resulting from different period lengths were quite different from their corresponding Macro schedules, specially in terms of required total runs and required PTOs. Different period lengths produced basically unchanged Macro and optimized Micro schedules for both garages. No significant correlation was found between the Macro schedules and the corresponding optimized Micro schedules for both garages under base parameter settings. Any Macro schedules had much lower total pay hours than corresponding optimized Micro schedules as well as the manual schedules for both garages, because total pay hours in any Macro schedules exclude sign-on allowances, pull-in and pull-out costs, and join-up costs.

Different input files still were unable to produce an acceptable optimized Micro schedule for Cabot Garage under current hard and soft rules and they also produced virtually unchanged optimized Micro schedules for Albany Garage. Different parameter lengths in the Macro files did create slightly different Macro schedules for both garages, however corresponding optimized Micro schedules were basically unchanged. Different fringe-benefits parameters in the Macro files also resulted in basically unchanged optimized Micro schedules for both garages. In addition, it seemed that the use of a global wage rate file or the use of different wage rates for FTOs and PTOs in the Macro file did not significantly affect the results under current hard and soft rules: different PTO wage rates still could not be used to control the number of required PTOs.

The relaxed FTO spread-length rule (from 11 hours to the legal limit of 13 hours) for Cabot Garage resulted in Micro schedules which were quite different from those created in previous tests. Manpower requirements (total runs and PTOs) in these Micro schedules were much closer to the desired level. An acceptable optimized Micro schedule which matched the manpower requirements (total runs and part-time duties) was also found. In addition, this relaxation helped HASTUS avoid generating any full-time duty (except for fixed FTOs) with duty lengths less than 7h50. The relaxation of the FTO spread length constraint above did not guarantee the result of an acceptable optimized Micro schedule for Cabot Garage: other appropriate parameter settings, such as a suitable period length, were also very important. The evaluation also showed that this relaxation usually resulted in greater total pay hours in a Cabot Garage optimized Micro schedule, by about 3% over the manual schedule.

The final set of evaluations showed that radically different work rules had little impact on Albany Garage Micro schedules. HASTUS did not generate any trippers for the Albany Garage Macro and Micro schedules, even if all restrictions against trippers were eliminated. In addition, the Micro schedules resulting from these changes were virtually unchanged, and no significant positive correlation was found between these Macro and Micro schedules. It was not obvious that Macro would reflect the impact resulting from different changes, although it was not possible to examine a wide range of Micro inputs to see if actual crew scheduling better approximating the Macro results could be obtained.

It seemed that Cabot Garage optimized Micro schedules were quite sensitive to certain parameter settings but insensitive to others. Only with very careful parameter settings could HASTUS create an acceptable automated crew schedule for Cabot Garage. In contrast, an acceptable and satisfactory automated crew schedule which had lower total pay hours and satisfactory required work force characteristics could readily be found for Albany Garage.

Throughout the research in this thesis, it seems that the computer-aided scheduling system is able to provide significant positive results in transit authorities. Savings on scheduling staff and time, improved scheduling productivity and efficiency can be expected from the employment of a modern computer-aided scheduling system. Such a system should also be able to provide feasible automated optimized crew schedules (and vehicle schedules) for either small or large garages. However, these systems (or at least HASTUS) may still not be very easy for schedulers to master and achieve the maximum benefits. Many parameters make it very difficult for schedulers to get maximum value from the system and discourage its use for the generation of feasible automated crew schedules. It is complicated to manipulate these parameters to create desired final automated crew schedules, because the interaction between these parameters and the impact from the use of different parameters are neither clear and nor easily determined. Many trial-and-errors during the automated crew scheduling process may be inevitable resulting in great difficulty in finding an acceptable automated crew schedule. In addition, if schedulers want to be able to take full advantages of the computer-aided scheduling system, authorities have to pay substantial attention to training to help them fully understand these parameters and inputs.

5.2 Further Research

The feasibility of these automated crew schedules found in this thesis do not imply total acceptability of these machine schedules to the MBTA. More adjustments and tests in the full use of the selection file and the cutting file are necessary to help find fully acceptable automated crew schedules for the MBTA. In addition, since an acceptable Cabot Garage optimized Micro schedule is very sensitive to parameter settings, more evaluation may be necessary for exploring possible key parameters or combinations of parameters for the generation of better Cabot Garage optimized Micro schedules. More evaluations are also necessary to examine if significant correlation can be found between Macro schedules and corresponding Micro schedules for the large garage, i.e. to examine if Macro is indeed capable of being an effective cost estimating tool for the MBTA.

Further research can also extend the evaluation to a more comprehensive study area including other bus garages and transit lines. Through this comprehensive evaluation, the potential impacts of HASTUS in the MBTA can be fully understood. This comprehensive evaluation is necessary for the MBTA to make the most out of its investment in HASTUS.

Another research area deals with vehicle scheduling. The evaluation of HASTUS in the thesis focus on the automatic crew scheduling functions (Micro and Macro). In fact, more saving of the crew schedule may derive from changes in the vehicle schedules. If the vehicle schedule can reduce an assignment of a bus, this can immediately save a duty in the crew schedule. Some adjustments in the vehicle schedule may also help reduce the make-up time in the crew schedule, or make a set of tighter schedules. These adjustments may also help HASTUS create acceptable and satisfying automatic optimized crew schedules for large garages. Therefore, further work can emphasize the relationship between the vehicle scheduling function and the crew scheduling function of HASTUS.

Further computer scheduling systems could be still more scheduler-friendly. Although the employment of the interactive environment is very important for success in the scheduling task, too many uncertainties may also confuse general schedulers and complicate the computer-aided scheduling process. For example, many available parameters and input files in HASTUS provide schedulers many useful options and tools to create desired crew runs. However, sometimes these options may confuse schedulers and complicate the use of HASTUS. In addition, similarity usually exists between parameters in different input files, such as different duty types defined in both parameter file and Macro file. The simplification of the (literally) hundreds of parameters in the various input files can greatly help save schedulers a significant amount of time and have easier control over desired final crew schedules. In the future, the integration of expert systems into the scheduling tool may be important to solve this kind of problem.

Of course, more detailed manuals or reports may be useful and important for schedulers. At the moment, current manuals provide simple explanations of basic commands rather than a comprehensive guide to obtaining full benefits from the system. If more information about the interaction between parameters (including different input files) and the resulting impacts are included in the manual, schedulers will have a better idea about how to use the system to obtained improved crew schedules.

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Appendix A: Terminology

Block: The duration from the beginning of a pull-out to the end of a pull-in for the identical vehicle. Pull-out means that a vehicle leaves the garage, while pull-in means that a vehicle returns to the garage.

A daily vehicle schedule can consist of one or several blocks. A block can be broken into pieces of work assigned to different drivers. It is sometimes called a "*string*" or a "running board" in [28][42].

Relief point: Locations where an operator can either leave the vehicle to have a break, or take over a vehicle to continue the operation -- the latter action is usually called *swing*: one operator takes over the vehicle while the original driver goes off duty. Sometimes, it stands for only intermediate stops or places to be allowed for a swing along the route excluding garages or terminals.

Piece of work: It is a period during which an operator remains with a vehicle without a break. It may start and end at a relief point or at a garage or depot. It is generally used in urban public transportation systems. The term *flight leg* that has a similar meaning used in airline crew scheduling.

Run: A daily crew schedule that consists of one or more pieces of work. It is generally used in urban transportation. It is also called *duty* but is different from the term *duty period* in the airlines. "*Runs*" can usually be classified as 3 types: straight duties, split duties, or trippers.

Straight duty: A crew schedule or a continuous working period that may contain a short break for rest or a meal (usually less than 1 hour). This break is usually a paid break.

Split duty: A crew schedule which contains at least two pieces of works with at least one longer time break between these pieces of works. This break is usually an unpaid break.

Tripper: A single-piece of work with a short duration, such as one or two hours. It is usually assigned as overtime work for a full-time operator or is performed by a part-time operator. It is sometimes called an "*extra*".

Spread time: The elapsed time from the beginning of a crew's daily working schedule to the end of it. It is different from *daily working hours* (the duty length, the accumulated time of an operator's run) which is the actual working time including platform and allowance times. Spread time may consist of several unpaid breaks. There is generally a limit to the maximum spread time with spread penalties also being paid for long spread duties. *Spread time* is also called spreadover.

Allowance: The legal paid time during which operators are not driving a vehicle outside the garage (depot), e.g. the report time (sign-on and sign-off), meal time, pull-out and pull-in time or travel time between relief points, etc.

Platform time: The period that an operator is on a vehicle.

Rotating roster: A system where work schedules over a certain period, such as a week, are assigned to operators in a rotating manner, so that every operator will have the same work load (and payment) and rest periods. A roster consists of several daily runs.

Appendix B: Relevant Union Contract Terms At the MBTA

1. Maximum hourly pay rate for full-time operator: $18.46 per hour.
2. Minimum hourly pay rate for part-time operator: $13.85 per hour.
3. Overtime rate: 1.5 times regular pay rate (for full-time duties).
4. Allowance for sign-on: 10 minutes for the bus and the street car system.
5. Maximum pay period without paying the overtime penalty: 7 hours 50 minutes plus 10-minute report time allowance.
6. The total duty-length of an overtime run is allowed from 7 hours 51 minutes to 8 hours 5 minutes (excluding the report allowance of 10 minutes).
7. The period when any relief is not allowed: 9:45 p.m. to 2:00 a.m. next morning.
8. Maximum piece length: 5 hours 59 minutes for full-time duties.
   5 hours 50 minutes for part-time duties.
9. Spread rate (for full-time duties): over 10 hours, 1.5 times regular pay rate;
   over 11 hours, 2.0 times regular pay rate.
10. The maximum spread time is 13 hours for both full-time and part-time operators.
11. A full-time duty that starts before 5:00 a.m. must have a minimum 20-minute paid mealbreak. For other types of full-time duties, any mealbreak which is 31 minutes or more can be unpaid.
12. No tripper is allowed.
13. Allowance for each swing (just full-time duties): 20 minutes premium at the current pay rate.

Appendix C

The Micro Files for the Evaluation

Appendix C1:

The Input Assignment File for Cabot Garage

```
                        total  extras
 1-piece  runs              0|    274
 2-piece  runs              0|      0
 3-piece  runs              0|      0
aver. platform time      0h00|   6h11

***  number of   runs      :    0
***  average platform time :  0h00.00

regular   runs                               time     average
               platform time                 0h00      0h00
               stand-by time                 0h00      0h00
               signon/off                    0h00      0h00
               travel time                   0h00      0h00
               joinup                        0h00      0h00
               paid meal break               0h00      0h00
               guarantee piece               0h00      0h00

               penalties
                 guarantee run               0h00      0h00
                 overtime                    0h00      0h00
                 spread  rate 1              0h00      0h00
                 spread  rate 2              0h00      0h00
                 spread  rate 3              0h00      0h00
                 other penalties             0h00      0h00

extras
               platform time              1693h09      6h11
               signon/off                    0h00      0h00
               guarantee piece               0h00      0h00
               overtime                    850h16      3h06

          total cost                           35,295.77$

          hourly rate                              20.78$

          average cost for regular   run            0.00$
```

Appendix C1-1:

The Output Assignment File for Cabot Garage

file abc44011 summary

	total	fto-str	fto-spl	pto	extras
1-piece runs	2	0	0	2	0
2-piece runs	188	26	108	54	0
3-piece runs	44	2	42	0	0
4-piece runs	4	0	4	0	0
aver. platform time	6h30	6h34	7h04	4h56	0h00

*** number of runs : 238
*** average platform time : 6h30.58

		time	average
regular runs			
	platform time	1550h53	6h31
	stand-by time	0h00	0h00
	signon/off	186h06	0h47
	travel time	0h00	0h00
	joinup	11h30	0h03
	paid meal break	14h05	0h04
	guarantee piece	0h00	0h00
	penalties		
	guarantee run	3h12	0h01
	overtime	32h55	0h08
	spread rate 1	9h44	0h02
	spread rate 2	0h00	0h00
	spread rate 3	0h00	0h00
	other penalties	33h23	0h08
extras			
	platform time	0h00	0h00
	signon/off	0h00	0h00
	guarantee piece	0h00	0h00
	overtime	0h00	0h00

total cost	32,488.43$
hourly rate	20.94$
average cost for regular run	136.51$

Appendix C2:

The Parameter File for Cabot Garage

hastus-micro

parameter list for file pmanual

pilot bonus for fulltime operators	(bonus-pilot-fto)	0.00
pilot bonus for parttime operators	(bonus-pilot-pto)	0.00
default layover before e-cut	(e-cut-layover)	0h00
early finishing runs	(early-run)	100P
flag for paying pilot bonus	(flag-pilot-bonus)	0
flag for paying relief allowance	(flag-relief-allow)	0
default deadhead time	(h-deadhead-default)	60
maximum length of a layover	(h-layover-length)	0h00
min and max layover allowed	(h-min-max-layover)	0.00 0h45
hourly pay rate for fto	(hourly-rate-fto)	18.46
hourly pay rate for pto	(hourly-rate-pto)	13.85
late beginning runs	(late-run)	200P
add pulls during runcut <= value	(max-pull-rel-time)	0h05
minimum pay time for a break	(min-paid-break)	0h00
option for calculating signon/off	(option-sign)	1
overtime rate or factor	(overtime-rate)	1.50
periods when reliefs are forbidden	(partition-forbidden)	945P 800X
period length for HASTUS-Macro	(period-length)	0h34
minimum piece length	(piece-min-length)	0h50
relief allowance	(relief-allowance)	0h01
report time for pull-outs	(report-pull)	0h10
morning rush hours	(rush-hour1)	630A 830A
afternoon rush hours	(rush-hour2)	330P 730P
add. report time for 2nd period pull	(second-period-pull)	0h05
slack allowed for relief	(shift-relief-max)	1h00
premium rate(s) for spread	(spread-rate)	10h00 1.50 11h00 2.00
swing allowance	(swing-allowance)	0h20
number of runs	(total-runs)	233

		fto1	fto2	fto3	pto1
guaranteed pay time for a run	(guarantee-run)	7h50	7h50	7h50	0h00
min and max joinup length	(joinup-length)	0h00 0h45	0h00 0h45	0h00 1h06	0h00 0h45
min and max mealbreak	(mealbreak)	0h20 0h42	0h23 4h00	0h23 4h00	0h00 10h00
min and max unpaid mealbreak	(mealbreak-unpaid)	0h00 0h00	0h31 4h00	0h31 4h00	0h31 10h00
min and max number of pieces in a run	(number-pieces)	2 3	2 2	3 6	1 4
max pay time without overtime	(overtime)	7h50	7h50	7h50	0h00
min and max paid time	(paid-time)	7h00 8h05	7h00 8h05	6h50 8h05	4h00 5h50
set associated with the run-type	(parameter-set)	fto-straight	fto-split	fto-split	pto
maximum piece length	(piece-max-length)	5h59	5h59	5h59	5h50
min and max platform time	(platform-time)	5h30 8h05	6h00 8h05	5h07 8h05	3h50 5h50
earliest and latest starting time	(range-begin)	400A 200X	501A 800X	501A 800X	501A 200X
earliest and latest finishing time	(range-end)	1130A 200X	1200A 800X	1200A 800X	900A 200X
min and max spread	(spread)	7h15 8h05	7h00 10h59	7h25 10h59	4h00 13h00
type description	(type-description)	fulltime	fulltime	fulltime	parttime
min and max number of runs	(type-number)	0 16	0 999	0 999	0 53

Appendix C2-1:

The Complete Parameter File for Cabot Garage

hastus-micro

parameter list for file pmanual

add new arcs	(add-arcs)	yes
pilot bonus for fulltime operators	(bonus-pilot-fto)	0.00
pilot bonus for parttime operators	(bonus-pilot-pto)	0.00
bonus for a run or a extra	(bonus-run)	0.00
cash accounting	(cash)	0h00
relief window during layovers	(cut-in-layover)	0h00 0h00
type of data	(data)	bus
default layover before e-cut	(e-cut-layover)	0h00
early finishing runs	(early-run)	100P
min and max number of extras	(extra-number)	0 0
internal penalty for extras	(extra-penalty)	10.00
pay factor for extras	(extra-rate)	1.50
slack time after f..end-of-service	(f-end-serv-after)	0h00
slack time before f..end-of-service	(f-end-serv-before)	0h00
flag for paying pilot bonus	(flag-pilot-bonus)	0
flag for paying relief allowance	(flag-relief-allow)	0
fringe-benefits	(fringe-benefits)	0.00
guaranteed pay time for a extra	(guarantee-extra)	0h00
guaranteed pay time for a piece	(guarantee-piece)	0h00
changing points defined by default	(h-change-points)	yes
ignore reliefs at ends of strings	(h-compress-garage)	0h00
default deadhead time	(h-deadhead-default)	60
maximum length of a layover	(h-layover-length)	0h00
length of paid break for straight run	(h-mealbreak)	0h30
min and max layover allowed	(h-min-max-layover)	0.00 0h45
number of min-layovers to consider	(h-nb-min-lay)	0
min-layover for h..sm command	(h-sm-min-layover)	0h00
latest hour for a.m. prep/stow times	(h-veh-p/s-hour)	1200P
veh prep time (am and pm)	(h-veh-prep-am/pm)	0h00 0h00
veh stow time (am and pm)	(h-veh-stow-am/pm)	0h00 0h00
hourly pay rate for fto	(hourly-rate-fto)	13.46
hourly pay rate for pto	(hourly-rate-pto)	13.85
payment option for an n-piece run	(joinup-payment)	1
penalty on n-piece runs	(joinup-penalty)	0.00
late beginning runs	(late-run)	200P
max length for non-partitioned string	(max-feasibility)	4h30
add pulls during runcut <= value	(max-pull-rel-time)	0h05
max travel time in a run	(maximum-travel-time)	2h00
window for the mealbreak	(mealbreak-window)	0h00 32h00
minimum length of a half-run	(min-half-run-length)	2h00
minimum pay time for a break	(min-paid-break)	0h00
minimum break between pieces	(minimum-travel-time)	0h00
pay differential for night runs	(night-differential)	empty vect.
relief option	(option-relief)	4
option for calculating signon/off	(option-sign)	1
overtime rate or factor	(overtime-rate)	1.50
maximum number of split runs	(partimer-nb)	0
periods when reliefs are forbidden	(partition-forbidden)	945P 800X
maximum reliefs in a string partition	(partition-max-piece)	7
max number of alt. string partitions	(partition-max-type)	20
max number of string partitions (total)	(partition-number)	1500

Appendix C2-1:

The Complete Parameter File for Cabot Garage

hastus-micro

parameter list for file pmanual

penalty on a piece	(partition-pen-ct)	5.00
penalty on the number of pieces	(partition-pen-nb)	1.00
min number of alt. string partitions	(partition-string-min)	3
period length for HASTUS-Macro	(period-length)	0h34
maximum number of pieces	(piece-max-number)	6
minimum piece length	(piece-min-length)	0h50
print option	(print-level)	5
relief allowance	(relief-allowance)	0h01
min. length to relieve in layover	(relief-in-layover)	32h00
permit removal of arcs from network	(remove-arcs)	no
report time for pull-outs	(report-pull)	0h10
contiguous days off in a roster	(roster-cont-days-off)	no
guaranteed time in a week (roster)	(roster-guarantee)	0h00
	(roster-nb-days)	1 5
minimum resr period (roster)	(roster-off-run)	0h00
latest end time for an unpaid break	(run-end-paid-break)	800X
morning rush hours	(rush-hour1)	630A 830A
afternoon rush hours	(rush-hour2)	330P 730P
add. report time for 2nd period pull	(second-period-pull)	0h05
slack allowed for relief	(shift-relief-max)	1h00
signon/off time at a garage	(signon/off-garage)	0h00 0h00
signon/off time at a relief point	(signon/off-relief)	0h00 0h00
bonus(es) for spread	(spread-bonus)	empty vect.
allowable spread (based on run end)	(spread-end)	empty vect.
premium rate(s) for spread	(spread-rate)	10h00 1.50
		11h00 2.00
maximum percentage of straights	(straight-max-percent)	100
minimum percentage of straights	(straight-min-percent)	0
straight deletion	(straight-over)	0
ranges for run summaries	(straight-summary)	empty vect.
swing allowance	(swing-allowance)	0h20
minimum length for a technical break	(technical-break)	0h00
number of runs	(total-runs)	233
travel time option for a joinup	(travel-joinup)	1
travel time option for a mealbreak	(travel-mealbreak)	2
maximum walking and slack time	(travel/slack)	0h00 0h00

		fto1	fto2	fto3	pto1
guaranteed pay time for a run	(guarantee-run)	7h50	7h50	7h50	0h00
maximum length of a half-run	(half-run-length)	5h59	5h59	5h59	5h50
min and max joinup length	(joinup-length)	0h00 0h45	0h00 0h45	0h00 1h06	0h00 0h45
min and max mealbreak	(mealbreak)	0h20 0h42	0h23 4h00	0h23 4h00	0h00 10h00
pay rate for a mealbreak	(mealbreak-rate)	1.00	1.00	1.00	0.00
min and max unpaid mealbreak	(mealbreak-unpaid)	0h00 0h00	0h31 4h00	0h31 4h00	0h31 10h00
min and max number of pieces in a run	(number-pieces)	2 3	2 2	3 6	1 4
max pay time without overtime	(overtime)	7h50	7h50	7h50	0h00
min and max paid time	(paid-time)	7h00 8h05	7h00 8h05	6h50 8h05	4h00 5h50
set associated with the run-type	(parameter-set)	fto-straight	fto-split	fto-split	pto
maximum piece length	(piece-max-length)	5h59	5h59	5h59	5h50

Appendix C2-1:

The Complete Parameter File for Cabot Garage

hastus-micro

parameter list for file pmanual

			fto1		fto2		fto3		pto1	
min and max platform time	(platform-time	)	5h30	8h05	6h00	8h05	5h07	8h05	3h50	5h50
earliest and latest starting time	(range-begin	)	400A	200X	501A	800X	501A	800X	501A	200X
earliest and latest finishing time	(range-end	)	1130A	200X	1200A	800X	1200A	800X	900A	200X
min and max spread	(spread	)	7h15	8h05	7h00	10h59	7h25	10h59	4h00	13h00
type description	(type-description	)	fulltime		fulltime		fulltime		parttime	
min and max number of runs	(type-number	)	0	16	0	999	0	999	0	53
uncovered window	(uncover-time	)	1200A	1200A	1200A	1200A	1200A	1200A	1200A	1200A

Appendix C3:

The Selection File for Cabot Garage

```
                                                          hastus-micro

file description :
Copied from sbc44111 -  12/06/94-16:19  strobe  Copied from sport2   -  11/30/

  description of selection file sbc441ew

 1 late spread
   pen  9999.9        run-spread         10h00-13h00        run-type             fto-split
                      run-end             900P- 200X

 2 avoid late spread
   pen    100.0       /hour for variation from              run-spread         0h00-10h00
                      run-type                fto-split     run-end            600P- 959P

 3 fto platform
   pen    100.0       /hour for variation from              run-platform-time  7h01- 7h20
                      run-type                fto-split

 4 fto platform
   pen    200.0       /hour for variation from              run-platform-time  7h21- 7h45
                      run-type                fto-split

 5 fto platform
   pen    300.0       /hour for variation from              run-platform-time  7h46- 8h05
                      run-type                fto-split

 6 schools
   pen   9999.0       run-number-pieces     0               routes             9700

 7 3-piece days
   pen   -125.0       run-number-pieces     3               run-type             fto-split

 8 pto platform
   pen    125.0       /hour for variation from              run-platform-time  4h40- 5h50
                      run-type              pto1

 9 pto platform
   pen    200.0       /hour for variation from              run-platform-time  5h00- 5h50
                      run-type              pto1

10 no straights
   pen   9999.9       run-type              fto-straight

11 late trippers
   pen   9999.0       run-number-pieces     0               piece-end          730P- 200X

12 non pm fto
   pen   9999.9       run-type              fto-split       run-end            800P- 200X
                      mealbreak-time      500P- 645P
```

Appendix C4:
The Cutting File for Cabot Garage

hastus-micro

```
file description :
Copied from tcabotew -  11/28/94-09:17  strobe  Copied from tcabot   -  11/08/

  description of cutting-types  file tcabot2

 1 pen  9999.9      cut-place          kneel             cut-relief       1200A- 800X

 2 pen  9999.9      cut-place          fhill             cut-relief       1200A- 800X

 3 pen  9999.9      cut-place          cntsq

 4 pen  9999.9      cut-relief-type    *     s           cut-relief        515P- 200X

 5 pen  9999.9      cut-relief-type    *     s           cut-relief        501A-1059A

 6 pen   500.0      cut-relief-type    *     s           cut-relief       1230P- 259P

 7 pen  9999.9      cut-place          harsq

 8 pen  9999.9      cut-place          bdfch

 9 pen  9999.0      string-end          600P- 930P       cut-relief        500P- 900P

10 pen  9999.9      cut-piece-length    0h01- 2h00       cut-relief        500P- 630P

11 pen  9999.9      string-route       22_               cut-relief-type  *     p
                    cut-piece          1015A-1052A
```

Appendix C5:

The Macro File for Cabot Garage

```
* test
def number-peak-hours 2
def peak-hour 1 7h45
def peak-hour 2 17h03
def signon-signoff 0h10 0h10
def guaranteed-piece 2h04
def max-feasibility 3h37
def no-piece-cut 4h08 8h16
def no-piece-cut 22h13 30h29
def hourly-rate 18.46
def number-types 6
constraint 1 spread 11h22 or less minimum 100.0 type 1 2 3 4 over 1 2 3 4
schedule file list
evaluate-agreement
*
* straight run
*
duty-type 1 fto category a
def range-start 0h00 4h39
def overtime 7h55 1.5
def number-pieces 2 2
def mealbreak-length 0h31 1h02
def duty-length 6h43
def piece-length 2h04 5h10
def max-spread 7h45
def fringe-benefits 50.0
*
* early regular split
*
duty-type 2 fto category a
def range-start 4h39 8h16
def number-pieces 2 2
def overtime 7h55 1.5
def duty-length 8h16
def mealbreak-length 0h31 1h02
def piece-length 2h04 5h10
def max-spread 11h22
def piece-peak 2 10
def spread-rate 10h20 1.5
def spread-rate 11h22 2.0
def fringe-benefits 35.0
*
* regular 3piece run
*
duty-type 3 fto category a
def range-start 5h10 8h16
def range-start 10h20 12h55
def overtime 7h55 1.5
def number-pieces 3 3
def duty-length 7h14
```

Appendix C5:

The Macro File for Cabot Garage

```
def mealbreak-length 1h33 2h35
def coffee-break 0h00 0h31
def max-spread 11h22
def piece-length 2h04 4h08
def piece-peak 3 2
def spread-rate 10h20 1.5
def spread-rate 11h22 2.0
def fringe-benefits 45.0
*
* late regular split
*
duty-type 4 fto category a
def range-start 12h55 16h32
def overtime 7h55 1.5
def number-pieces 2 2
def duty-length 8h16
def mealbreak-length 0h31 1h02
def piece-length 2h04 5h10
def max-spread 10h20
def piece-peak 2 10
def spread-rate 10h20 1.5
def spread-rate 11h22 2.0
def fringe-benefits 30.0
*
* partimer 2 pieces
*
duty-type 5 pto category b
def range-start 5h10 7h45
def overtime 1h00 1.0
def mealbreak-length 4h08 7h14
def piece-length 2h04 4h39
def max-spread 12h55
def number-pieces 2 2
def duty-length 5h41
def piece-peak 2 2
def fringe-benefits 75.0
*
* partimer 1 piece
*
duty-type 6 pto category b
def number-pieces 0 0
def tripper-max-length 4h39
def tripper-factor 15.0 3h37
def tripper-dif-penalty 15.0
def fringe-benefits 100.0
execution
```

Appendix C6:

The Input Assignment File for Albany Garage

```
                              total extras
 1-piece  runs                  0|    155
 2-piece  runs                  0|      0
 3-piece  runs                  0|      0
aver. platform time          0h00|   5h29

***  number of   runs      :     0
***  average platform time :  0h00.00

regular   runs                                  time     average
               platform time                    0h00       0h00
               stand-by time                    0h00       0h00
               signon/off                       0h00       0h00
               travel time                      0h00       0h00
               joinup                           0h00       0h00
               paid meal break                  0h00       0h00
               guarantee piece                  0h00       0h00

               penalties
                 guarantee run                  0h00       0h00
                 overtime                       0h00       0h00
                 spread  rate 1                 0h00       0h00
                 spread  rate 2                 0h00       0h00
                 spread  rate 3                 0h00       0h00
                 other penalties                0h00       0h00

extras
               platform time                  850h07       5h29
               signon/off                       0h00       0h00
               guarantee piece                  0h00       0h00
               overtime                       425h40       2h45

          total cost                               17,669.67$

          hourly rate                                  20.78$

          average cost for regular   run                0.00$
```

Appendix C6-1:

The Output Assignment File for Albany Garage

```
                     file aamanual summary

                      total fto-str fto-spl      pto   extras
 1-piece  runs            0       0       0        0|       0
 2-piece  runs          114      13      57       44|       0
 3-piece  runs           15       0      14        1|       0
 4-piece  runs            1       0       1        0|       0
aver. platform time    5h43    6h05    6h30     4h21|    0h00

***  number of   runs      :  130
***  average platform time :  5h43.07

regular   runs                                time     average
               platform time               743h27       5h43
               stand-by time                 0h00       0h00
               signon/off                  160h06       1h14
               travel time                   0h00       0h00
               joinup                        4h48       0h02
               paid meal break               7h25       0h03
               guarantee piece               0h00       0h00

               penalties
                 guarantee run              11h35       0h05
                 overtime                    8h38       0h04
                 spread  rate 1              1h48       0h01
                 spread  rate 2              0h00       0h00
                 spread  rate 3              0h00       0h00
                 other penalties            15h46       0h07

extras
               platform time                 0h00       0h00
               signon/off                    0h00       0h00
               guarantee piece               0h00       0h00
               overtime                      0h00       0h00

          total cost                          16,389.33$

          hourly rate                             22.04$

          average cost for regular   run         126.07$
```

Appendix C7:

The Parameter File for Albany Garage

hastus-micro

parameter list for file pamanual

pilot bonus for fulltime operators	(bonus-pilot-fto)	0.00
pilot bonus for parttime operators	(bonus-pilot-pto)	0.00
default layover before e-cut	(e-cut-layover)	0h05
early finishing runs	(early-run)	100P
flag for paying pilot bonus	(flag-pilot-bonus)	0
flag for paying relief allowance	(flag-relief-allow)	0
default deadhead time	(h-deadhead-default)	60
maximum length of a layover	(h-layover-length)	0h00
min and max layover allowed	(h-min-max-layover)	0.00 0h00
hourly pay rate for fto	(hourly-rate-fto)	18.46
hourly pay rate for pto	(hourly-rate-pto)	13.85
late beginning runs	(late-run)	200P
add pulls during runcut <= value	(max-pull-rel-time)	0h05
minimum pay time for a break	(min-paid-break)	0h00
option for calculating signon/off	(option-sign)	1
overtime rate or factor	(overtime-rate)	1.50
periods when reliefs are forbidden	(partition-forbidden)	945P 800X
period length for HASTUS-Macro	(period-length)	0h34
minimum piece length	(piece-min-length)	0h50
relief allowance	(relief-allowance)	0h01
report time for pull-outs	(report-pull)	0h10
morning rush hours	(rush-hour1)	630A 830A
afternoon rush hours	(rush-hour2)	330P 730P
add. report time for 2nd period pull	(second-period-pull)	0h05
slack allowed for relief	(shift-relief-max)	1h00
premium rate(s) for spread	(spread-rate)	10h00 1.50 11h00 2.00
swing allowance	(swing-allowance)	0h20
number of runs	(total-runs)	119

fto-straight :		fto1	fto4
guaranteed pay time for a run	(guarantee-run)	7h50	7h50
min and max joinup length	(joinup-length)	0h00 0h00	0h00 0h44
min and max mealbreak	(mealbreak)	0h23 0h45	0h23 0h46
min and max unpaid mealbreak	(mealbreak-unpaid)	0h00 0h00	0h00 0h00
min and max number of pieces in a run	(number-pieces)	2 2	2 3
max pay time without overtime	(overtime)	7h50	7h50
min and max paid time	(paid-time)	7h00 8h05	7h00 8h05
set associated with the run-type	(parameter-set)	fto-straight	fto-straight
maximum piece length	(piece-max-length)	5h59	5h59
min and max platform time	(platform-time)	5h30 8h05	4h48 8h05
earliest and latest starting time	(range-begin)	1200A 500A	501A 1130P
earliest and latest finishing time	(range-end)	1200A 800X	1200A 800X
min and max spread	(spread)	7h15 8h05	7h15 8h05
type description	(type-description)	fulltime	fulltime
min and max number of runs	(type-number)	0 999	0 999

Appendix C7:

The Parameter File for Albany Garage

hastus-micro

fto-split :			fto2	fto3
guaranteed pay time for a run	(guarantee-run	)	7h50	7h50
min and max joinup length	(joinup-length	)	0h00 0h45	0h00 0h45
min and max mealbreak	(mealbreak	)	0h25 4h00	0h25 4h00
min and max unpaid mealbreak	(mealbreak-unpaid	)	0h31 4h00	0h31 4h00
min and max number of pieces in a run	(number-pieces	)	2 2	3 6
max pay time without overtime	(overtime	)	7h50	7h50
min and max paid time	(paid-time	)	7h00 8h05	7h00 8h05
set associated with the run-type	(parameter-set	)	fto-split	fto-split
maximum piece length	(piece-max-length	)	5h59	5h59
min and max platform time	(platform-time	)	4h00 8h05	4h40 8h05
earliest and latest starting time	(range-begin	)	501A 800X	501A 800X
earliest and latest finishing time	(range-end	)	1200A 800X	1200A 800X
min and max spread	(spread	)	7h15 10h59	7h25 10h59
type description	(type-description	)	fulltime	fulltime
min and max number of runs	(type-number	)	0 999	0 999

pto :			pto1	pto2
guaranteed pay time for a run	(guarantee-run	)	0h00	0h00
min and max joinup length	(joinup-length	)	0h00 0h45	0h00 0h45
min and max mealbreak	(mealbreak	)	0h00 0h00	0h00 10h00
min and max unpaid mealbreak	(mealbreak-unpaid	)	0h00 0h00	0h31 10h00
min and max number of pieces in a run	(number-pieces	)	1 4	2 4
max pay time without overtime	(overtime	)	0h00	0h00
min and max paid time	(paid-time	)	4h00 5h50	4h00 5h50
set associated with the run-type	(parameter-set	)	pto	pto
maximum piece length	(piece-max-length	)	5h50	5h50
min and max platform time	(platform-time	)	3h50 5h50	3h23 5h50
earliest and latest starting time	(range-begin	)	500A 430P	500A 400P
earliest and latest finishing time	(range-end	)	1200A 945P	400P 945P
min and max spread	(spread	)	4h00 5h50	5h51 13h00
type description	(type-description	)	parttime	parttime
min and max number of runs	(type-number	)	0 9	0 43

Appendix C7-1:

The Complete Parameter File for Albany Garage

hastus-micro

parameter list for file pamanual

add new arcs	(add-arcs)	yes
pilot bonus for fulltime operators	(bonus-pilot-fto)	0.00
pilot bonus for parttime operators	(bonus-pilot-pto)	0.00
bonus for a run or a extra	(bonus-run)	0.00
cash accounting	(cash)	0h00
relief window during layovers	(cut-in-layover)	0h00 0h00
type of data	(data)	bus
default layover before e-cut	(e-cut-layover)	0h05
early finishing runs	(early-run)	100P
min and max number of extras	(extra-number)	0 0
internal penalty for extras	(extra-penalty)	10.00
pay factor for extras	(extra-rate)	1.50
slack time after f..end-of-service	(f-end-serv-after)	0h00
slack time before f..end-of-service	(f-end-serv-before)	0h00
flag for paying pilot bonus	(flag-pilot-bonus)	0
flag for paying relief allowance	(flag-relief-allow)	0
fringe-benefits	(fringe-benefits)	0.00
guaranteed pay time for a extra	(guarantee-extra)	0h00
guaranteed pay time for a piece	(guarantee-piece)	0h00
changing points defined by default	(h-change-points)	yes
ignore reliefs at ends of strings	(h-compress-garage)	0h00
default deadhead time	(h-deadhead-default)	60
maximum length of a layover	(h-layover-length)	0h00
length of paid break for straight run	(h-mealbreak)	0h30
min and max layover allowed	(h-min-max-layover)	0.00 0h00
number of min-layovers to consider	(h-nb-min-lay)	0
min-layover for h..sm command	(h-sm-min-layover)	0h00
latest hour for a.m. prep/stow times	(h-veh-p/s-hour)	1200P
veh prep time (am and pm)	(h-veh-prep-am/pm)	0h00 0h00
veh stow time (am and pm)	(h-veh-stow-am/pm)	0h00 0h00
hourly pay rate for fto	(hourly-rate-fto)	18.46
hourly pay rate for pto	(hourly-rate-pto)	13.85
payment option for an n-piece run	(joinup-payment)	1
penalty on n-piece runs	(joinup-penalty)	0.00
late beginning runs	(late-run)	200P
max length for non-partitioned string	(max-feasibility)	4h30
add pulls during runcut <= value	(max-pull-rel-time)	0h05
max travel time in a run	(maximum-travel-time)	2h00
window for the mealbreak	(mealbreak-window)	0h00 32h00
minimum length of a half-run	(min-half-run-length)	2h00
minimum pay time for a break	(min-paid-break)	0h00
minimum break between pieces	(minimum-travel-time)	0h00
pay differential for night runs	(night-differential)	empty vect.
relief option	(option-relief)	4
option for calculating signon/off	(option-sign)	1
overtime rate or factor	(overtime-rate)	1.50
maximum number of split runs	(partimer-nb)	0
periods when reliefs are forbidden	(partition-forbidden)	945P 800X
maximum reliefs in a string partition	(partition-max-piece)	7
max number of alt. string partitions	(partition-max-type)	20
max number of string partitions (total)	(partition-number)	1500

Appendix C7-1:

The Complete Parameter File for Albany Garage

hastus-micro

parameter list for file pamanual

penalty on a piece	(partition-pen-ct)	5.00
penalty on the number of pieces	(partition-pen-nb)	1.00
min number of alt. string partitions	(partition-string-min)	3
period length for HASTUS-Macro	(period-length)	0h34
maximum number of pieces	(piece-max-number)	6
minimum piece length	(piece-min-length)	0h50
print option	(print-level)	5
relief allowance	(relief-allowance)	0h01
min. length to relieve in layover	(relief-in-layover)	32h00
permit removal of arcs from network	(remove-arcs)	no
report time for pull-outs	(report-pull)	0h10
contiguous days off in a roster	(roster-cont-days-off)	no
guaranteed time in a week (roster)	(roster-guarantee)	0h00
	(roster-nb-days)	1 5
minimum resr period (roster)	(roster-off-run)	0h00
latest end time for an unpaid break	(run-end-paid-break)	800X
morning rush hours	(rush-hour1)	630A 830A
afternoon rush hours	(rush-hour2)	330P 730P
add. report time for 2nd period pull	(second-period-pull)	0h05
slack allowed for relief	(shift-relief-max)	1h00
signon/off time at a garage	(signon/off-garage)	0h00 0h00
signon/off time at a relief point	(signon/off-relief)	0h00 0h00
bonus(es) for spread	(spread-bonus)	empty vect.
allowable spread (based on run end)	(spread-end)	empty vect.
premium rate(s) for spread	(spread-rate)	10h00 1.50
		11h00 2.00
maximum percentage of straights	(straight-max-percent)	100
minimum percentage of straights	(straight-min-percent)	0
straight deletion	(straight-over)	0
ranges for run summaries	(straight-summary)	empty vect.
swing allowance	(swing-allowance)	0h20
minimum length for a technical break	(technical-break)	0h00
number of runs	(total-runs)	119
travel time option for a joinup	(travel-joinup)	1
travel time option for a mealbreak	(travel-mealbreak)	2
maximum walking and slack time	(travel/slack)	0h00 0h00

fto-straight :		fto1	fto4
guaranteed pay time for a run	(guarantee-run)	7h50	7h50
maximum length of a half-run	(half-run-length)	5h59	5h59
min and max joinup length	(joinup-length)	0h00 0h00	0h00 0h44
min and max mealbreak	(mealbreak)	0h23 0h45	0h23 0h46
pay rate for a mealbreak	(mealbreak-rate)	1.00	1.00
min and max unpaid mealbreak	(mealbreak-unpaid)	0h00 0h00	0h00 0h00
min and max number of pieces in a run	(number-pieces)	2 2	2 3
max pay time without overtime	(overtime)	7h50	7h50
min and max paid time	(paid-time)	7h00 8h05	7h00 8h05
set associated with the run-type	(parameter-set)	fto-straight	fto-straight
maximum piece length	(piece-max-length)	5h59	5h59

Appendix C7-1:

The Complete Parameter File for Albany Garage

hastus-micro

parameter list for file pamanual

fto-straight :		fto1	fto4
min and max platform time	(platform-time)	5h30 8h05	4h48 8h05
earliest and latest starting time	(range-begin)	1200A 500A	501A 1130P
earliest and latest finishing time	(range-end)	1200A 800X	1200A 800X
min and max spread	(spread)	7h15 8h05	7h15 8h05
type description	(type-description)	fulltime	fulltime
min and max number of runs	(type-number)	0 999	0 999
uncovered window	(uncover-time)	1200A 1200A	1200A 1200A

fto-split :		fto2	fto3
guaranteed pay time for a run	(guarantee-run)	7h50	7h50
maximum length of a half-run	(half-run-length)	5h59	5h59
min and max joinup length	(joinup-length)	0h00 0h45	0h00 0h45
min and max mealbreak	(mealbreak)	0h25 4h00	0h25 4h00
pay rate for a mealbreak	(mealbreak-rate)	1.00	1.00
min and max unpaid mealbreak	(mealbreak-unpaid)	0h31 4h00	0h31 4h00
min and max number of pieces in a run	(number-pieces)	2 2	3 6
max pay time without overtime	(overtime)	7h50	7h50
min and max paid time	(paid-time)	7h00 8h05	7h00 8h05
set associated with the run-type	(parameter-set)	fto-split	fto-split
maximum piece length	(piece-max-length)	5h59	5h59
min and max platform time	(platform-time)	4h00 8h05	4h40 8h05
earliest and latest starting time	(range-begin)	501A 800X	501A 800X
earliest and latest finishing time	(range-end)	1200A 800X	1200A 800X
min and max spread	(spread)	7h15 10h59	7h25 10h59
type description	(type-description)	fulltime	fulltime
min and max number of runs	(type-number)	0 999	0 999
uncovered window	(uncover-time)	1200A 1200A	1200A 1200A

pto :		pto1	pto2
guaranteed pay time for a run	(guarantee-run)	0h00	0h00
maximum length of a half-run	(half-run-length)	5h50	5h50
min and max joinup length	(joinup-length)	0h00 0h45	0h00 0h45
min and max mealbreak	(mealbreak)	0h00 0h00	0h00 10h00
pay rate for a mealbreak	(mealbreak-rate)	0.00	0.00
min and max unpaid mealbreak	(mealbreak-unpaid)	0h00 0h00	0h31 10h00
min and max number of pieces in a run	(number-pieces)	1 4	2 4
max pay time without overtime	(overtime)	0h00	0h00
min and max paid time	(paid-time)	4h00 5h50	4h00 5h50
set associated with the run-type	(parameter-set)	pto	pto
maximum piece length	(piece-max-length)	5h50	5h50
min and max platform time	(platform-time)	3h50 5h50	3h23 5h50
earliest and latest starting time	(range-begin)	500A 430P	500A 400P
earliest and latest finishing time	(range-end)	1200A 945P	400P 945P

Appendix C7-1:

The Complete Parameter File for Albany Garage

hastus-micro

parameter list for file pamanual

pto :			pto1		pto2	
min and max spread	(spread	)	4h00	5h50	5h51	13h00
type description	(type-description	)	parttime		parttime	
min and max number of runs	(type-number	)	0	9	0	43
uncovered window	(uncover-time	)	1200A	1200A	1200A	1200A

Appendix C8:

The Selection File for Albany Garage

```
                                                      hastus-micro

file description :
Copied from sbc25011 -  12/15/94-13:54  strobe  Copied from sbc44111 -  12/06/

  description of selection file sba25011

 1 late spread
   pen  9999.9      run-spread         10h00-13h00      run-type            fto-split
                    run-end             900P- 200X

 2 avoid late spread
   pen   100.0      /hour for variation from            run-spread         0h00-10h00
                    run-type              fto-split     run-end            600P- 959P

 3 schools
   pen  9999.0      run-number-pieces     0             routes             9700

 4 no straights
   pen  9999.9      run-type              fto-straight

 5 late trippers
   pen  9999.0      run-number-pieces     0             piece-end          730P- 200X

 6 non pm fto
   pen  9999.9      run-type              fto-split     run-end            800P- 200X
                    mealbreak-time      500P- 645P
```

Appendix C9:

The Cutting File for Albany Garage

```
                                                 hastus-micro

file description :
Copied from talbny   -  07/01/92-08:21  strobe  Copied from talbny   -  09/25/

  description of cutting-types  file talbany

 1 pen  9999.0      cut-place       needj             cut-relief      1200A- 800X

 2 pen  9999.0      cut-place       aubnd             cut-relief      1200A- 800X

 3 pen  9999.0      cut-place       walth             cut-relief      1200A- 800X

 4 pen  9999.0      cut-relief       515P- 730P

 5 pen  9999.0      cut-place       brway             cut-relief      1200A- 800X

 6 pen  9999.0      cut-place       oaksq             cut-relief      1200A- 800X

 7 pen   100.0      cut-place       wtryd             cut-relief      1200A- 800X

 8 pen  9999.0      cut-place       kneel             cut-relief      1200A- 800X

 9 pen  9999.0      cut-place       wnwtn             cut-relief      1200A- 800X

10 pen   100.0      cut-place       brctr             cut-relief      1200A- 800X

11 pen  9999.0      cut-place       wnshp             cut-relief      1200A- 800X

12 pen  9999.0      cut-place       sosta             cut-relief      1200A- 800X

13 pen  9999.9      cut-relief-type *     s

14 pen  9999.9      cut-place       cabgr

15 pen   900.0      cut-place       cntsq             cut-relief      1200A- 800X

16 pen  9999.0      string-route    3041              cut-place       nwcor
```

Appendix C10:

The Macro File for Albany Garage

```
* test
def number-peak-hours 2
def peak-hour 1 7h22
def peak-hour 2 17h34
def signon-signoff 0h10 0h10
def guaranteed-piece 1h42
def max-feasibility 3h24 15.0
def no-piece-cut 6h48 9h04
def no-piece-cut 17h00 19h16
def no-piece-cut 22h06 30h02
def pieces-penalty 3h24 0.01
def hourly-rate 18.46
def number-types 3
def tripper-exist-block no
def tripper-peak yes
def tripper-dif-penalty 15.0
def tripper-max-length 10h46
def tripper-factor 1.3 2h50
constraint 1 spread 11h20 or less minimum 100.0 type 1 2 over 1 2
schedule file list
charac-schedule
evaluate-agreement
*
* regular early fto
*
duty-type 1 fto category a
def range-start 0h00 5h06
def number-pieces 2 3
def duty-length 6h48
def overtime 7h50 1.5
def mealbreak-length 0h34 0h34
def break-worked 0h00 1.0
def coffee-break 0h34 0h34
def piece-length 1h08 5h40
def half-duty-length 1h08 5h40
def max-spread 7h56
def piece-peak 3 2
def piece-block 3 1
def fringe-benefits 50.0
*
* regular late fto
*
duty-type 2 fto category a
def range-start 5h06 17h00
def number-pieces 2 3
def duty-length 6h48
def overtime 7h50 1.5
def mealbreak-length 1h08 3h24
def coffee-break 0h34 0h34
def piece-length 1h08 5h40
```

Appendix C10:

The Macro File for Albany Garage

```
def half-duty-length 1h08 5h40
def max-spread 10h46
def piece-peak 3 2
def spread-rate 10h12 1.5
def spread-rate 11h20 2.0
def fringe-benefits 50.0
*
* 2piece partimer
*
duty-type 3 pto category b
def range-start 5h06 7h56
def number-pieces 2 2
def min-work-time 4h32
def duty-length 5h40
def mealbreak-length 6h14 10h12
def piece-length 1h08 5h40
def piece-peak 2 10
def max-spread 13h02
def max-number-drivers 45
def fringe-benefits 65.0
execution
```

Appendix D

New Micro Files for Cabot Garage

Appendix D1:

The Parameter File for Cabot Garage

pilot bonus for fulltime operators	(bonus-pilot-fto)	0.00
pilot bonus for parttime operators	(bonus-pilot-pto)	0.00
default layover before e-cut	(e-cut-layover)	0h00
early finishing runs	(early-run)	100P
flag for paying pilot bonus	(flag-pilot-bonus)	0
flag for paying relief allowance	(flag-relief-allow)	0
default deadhead time	(h-deadhead-default)	60
maximum length of a layover	(h-layover-length)	0h00
min and max layover allowed	(h-min-max-layover)	0.00 0h45
hourly pay rate for fto	(hourly-rate-fto)	18.46
hourly pay rate for pto	(hourly-rate-pto)	13.85
late beginning runs	(late-run)	200P
add pulls during runcut <= value	(max-pull-rel-time)	0h05
minimum pay time for a break	(min-paid-break)	0h00
option for calculating signon/off	(option-sign)	1
overtime rate or factor	(overtime-rate)	1.50
periods when reliefs are forbidden	(partition-forbidden)	945P 800X
period length for HASTUS-Macro	(period-length)	0h34
minimum piece length	(piece-min-length)	0h50
relief allowance	(relief-allowance)	0h01
report time for pull-outs	(report-pull)	0h10
morning rush hours	(rush-hour1)	630A 930A
afternoon rush hours	(rush-hour2)	330P 630P
add. report time for 2nd period pull	(second-period-pull)	0h05
slack allowed for relief	(shift-relief-max)	1h00
premium rate(s) for spread	(spread-rate)	10h00 1.50
		11h00 2.00
swing allowance	(swing-allowance)	0h20
number of runs	(total-runs)	238

		fto1	fto2	fto3	pto1
guaranteed pay time for a run	(guarantee-run)	7h50	7h50	7h50	0h00
min and max joinup length	(joinup-length)	0h00 0h45	0h00 0h45	0h00 1h06	0h00 0h45
min and max mealbreak	(mealbreak)	0h20 0h42	0h23 4h00	0h23 4h00	0h00 10h00
min and max unpaid mealbreak	(mealbreak-unpaid)	0h00 0h00	0h31 4h00	0h31 4h00	0h31 10h00
min and max number of pieces in a run	(number-pieces)	2 3	2 2	3 6	1 4
max pay time without overtime	(overtime)	7h50	7h50	7h50	0h00
min and max paid time	(paid-time)	7h50 8h05	7h50 8h05	7h50 8h05	4h00 5h50
set associated with the run-type	(parameter-set)	fto-straight	fto-split	fto-split	pto
maximum piece length	(piece-max-length)	5h59	5h59	5h59	5h50
min and max platform time	(platform-time)	5h30 8h05	6h00 8h05	5h07 8h05	3h50 5h50
earliest and latest starting time	(range-begin)	400A 200X	501A 800X	501A 800X	501A 200X
earliest and latest finishing time	(range-end)	1130A 200X	1200A 800X	1200A 800X	900A 200X
min and max spread	(spread)	7h00 13h00	7h00 13h00	7h00 13h00	4h00 13h00
type description	(type-description)	fulltime	fulltime	fulltime	parttime
min and max number of runs	(type-number)	0 13	0 999	0 999	0 56

Appendix D2:
The Selection File for Cabot Garage

```
1 late spread
  pen  9999.9       run-spread          10h00-13h00       run-type          fto-split
                    run-end              900P- 200X

2 avoid late spread
  pen   100.0       /hour for variation from              run-spread        0h00-10h00
                    run-type              fto-split       run-end           600P- 959P

3 schools
  pen  9999.0       run-number-pieces     0               routes            9700

4 3-piece days
  pen  -125.0       run-number-pieces     3               run-type          fto-split

5 late trippers
  pen  9999.0       run-number-pieces     0               piece-end         730P- 200X

6 non pm fto
  pen  9999.9       run-type              fto-split       run-end           800P- 200X
                    mealbreak-time      500P- 645P
```

Appendix D3:

The Macro File for Cabot Garage

```
* test
def number-peak-hours 2
def peak-hour 1 7h22
def peak-hour 2 17h00
def signon-signoff 0h10 0h10
def guaranteed-piece 1h42
def max-feasibility 4h32
def no-piece-cut 4h32 7h56
def no-piece-cut 22h06 30h02
def number-types 6
constraint 1 spread 13h02 or less minimum 100.0 type 1 2 3 4 over 1 2 3 4
schedule file list
evaluate-agreement
*
* straight run
*
duty-type 1 fto category a
def range-start 0h00 5h06
def overtime 7h50 1.5
def number-pieces 2 2
def mealbreak-length 0h34 1h08
def duty-length 8h30
def piece-length 2h16 5h40
def max-spread 13h02
def hourly-rate 18.46
def fringe-benefits 50.0
*
* early regular split
*
duty-type 2 fto category a
def range-start 4h32 8h30
def number-pieces 2 2
def overtime 7h50 1.5
def duty-length 8h30
def mealbreak-length 0h34 1h42
def piece-length 1h42 5h40
def max-spread 13h02
def spread-rate 10h12 1.5
def spread-rate 11h20 2.0
def hourly-rate 18.46
def fringe-benefits 35.0
*
* regular 3piece run
*
duty-type 3 fto category a
def range-start 4h32 8h30
def range-start 10h12 11h54
def overtime 7h50 1.5
def number-pieces 3 3
def duty-length 7h22
```

Appendix D3:

The Macro File for Cabot Garage

```
def mealbreak-length 1h42 2h16
def max-spread 13h02
def piece-length 1h42 3h58
def spread-rate 10h12 1.5
def spread-rate 11h20 2.0
def hourly-rate 18.46
def fringe-benefits 45.0
*
* late regular split
*
duty-type 4 fto category a
def range-start 13h02 16h26
def overtime 7h50 1.5
def number-pieces 2 2
def duty-length 8h30
def mealbreak-length 0h34 1h08
def piece-length 1h42 5h40
def max-spread 13h02
def spread-rate 10h12 1.5
def spread-rate 11h20 2.0
def hourly-rate 18.46
def fringe-benefits 30.0
*
* partimer 2 pieces
*
duty-type 5 pto category b
def range-start 5h06 7h56
def mealbreak-length 4h32 7h22
def piece-length 1h42 5h40
def max-spread 13h02
def number-pieces 2 2
def duty-length 6h14
def piece-peak 2 2
def max-number-duties 56
def hourly-rate 13.85
def fringe-benefits 100.0
*
* partimer 1 piece
*
duty-type 6 pto category b
def number-pieces 0 0
def tripper-max-length 4h32
def tripper-factor 15.0 3h58
def tripper-dif-penalty 15.0
def fringe-benefits 200.0
execution
```

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