Analysis of Real Time Operations Control Strategies for Tren Urbano

by

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Abstract

Rail systems are frequently subject to disturbances (such as power failures, door malfunctioning and signal problems, to mention a few) that affect the service quality. During a disruption, the system controller makes corrective actions in order to minimize its impact on service quality. However, in a situation where the system performance is subject to financial incentives and penalties, the controller is expected to make control decisions that minimize the financial impact of the disruption which will depend on structure of the incentive and penalty provisions.

This thesis reviews the incentive/penalty clauses included in Tren Urbano's Operations and Maintenance Contract for on-time performance, and discusses how they are likely to affect the decisions made by the contractor when a disruption occurs in the system. The control decisions resulting from the contractor's point of view will be compared to the optimal control decisions that minimize the negative impacts of the disruption on the level of service. This comparison will be used to develop a proposal for revised contract terms to address the contractor's interests along with both the owner's and passenger's interests. Since Tren Urbano is the first privately contracted rail system, which will operate in North America, this thesis represents the first attempt to analyze the impact of such incentive and penalty clauses on service quality.

The results from the comparison between the optimal control strategies with the Tren Urbano hypothetical solution showed that the optimal control strategies resulted in greater passenger waiting time savings, ranging from 4%-33%. Proposals are developed to modify the contract terms as well as the incentive/penalty structure in order to create a set of new contract provisions where the contractor's interest are more perfectly aligned with the owner's objectives and passengers' expectations.

Thesis Supervisor: Nigel H.M. Wilson
Tittle: Professor of Civil and Environmental Engineering

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First, thank you, God... because you guided me through all these years of hard work, and have given me the strength to never look back. It never been easy, but you are always by my side whispering to my ear how important this is for my future... Please stay by my side in the years to come...

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Chapter 1:

Introduction

Rail systems are frequently subject to disturbances (such as power failures, door malfunctioning and signal problems, to mention a few) that affect the service quality. During a disruption, the system controller makes corrective actions in order to minimize its impact on service quality. However, in a situation where the system performance is subject to financial incentives and penalties, the controller is expected to make control decisions that minimize the financial impact of the disruption which will depend on structure of the incentive and penalty provisions.

This thesis will review the incentive/penalty clauses included in Tren Urbano's Operations and Maintenance Contract for on-time performance, and discuss how they are likely to affect the decisions made by the contractor when a disruption occurs in the system. The control decisions resulting from the contractor's point of view will be compared to the optimal control decisions that minimize the negative impacts of the disruption on the level of service. This comparison will be used to develop a proposal for revised contract terms to address both the contractor's interests and the owner and passenger's interests. Since Tren Urbano is the first privately contracted rail system, which will operate in North America, this thesis represents the first attempt to analyze the impact of such incentive and penalty clauses on service quality.

1.1 The Tren Urbano System

The San Juan Metropolitan Area (SJMA) is located in the north of Puerto Rico, and consists of 13 municipalities, totaling 400 square miles. The population in this region is about 1.3 million (according to the 1990 census), which represents 1/3 of the total population of the island. San Juan is one of the most densely populated regions in the United States. According to the Final Environmental Impact Statement (FEIS, 1995) for the Tren Urbano Project, 60% of the population in this region resides in the municipalities of San Juan, Bayamón and Carolina. Moreover, these three municipalities account for 83% of the employment in the region, with San Juan alone accounting for 63% of the regional employment. In San Juan, 90% of work trips are made by car, causing heavy congestion during the morning and afternoon peak periods. From the FEIS, 1/3 of the intersections in the Tren Urbano corridor operate with a level of service F, which is characterized by the unstable flow of vehicles, long queues, and stop-and-go movement[1]; around 2/3 of the roadways are operating with volumes above 60% of capacity. In addition, from 1990 census data, there are 0.405 vehicles per person. These numbers indicate the high dependence on the car found in the San Juan Metropolitan Area.

Buses and públicos (a type of jitney service) currently represent the other transportation alternatives for moving around San Juan. Unfortunately, the bus system experienced a long period of declining ridership up to the mid 1990s as shown in a study that compares ridership in 1989/90 and 1994 (Multisystems, 1996). Reasons for this decline in ridership included poor frequency, poor service design, low speed, and poor schedule adherence. Recently, however, the bus system has gone through a series of improvements including the creation of Transit Centers, replacement of buses that reduced the average age to 4.5 years, and restructuring of the bus services. The Transit Center concept refers to the creation of major transit 'stations' located at major activity centers in the region that serve not only as transfer points but also as bus terminal and

[1] Transportation Research Board. *Highway Capacity Manual – Special Report 209*. 1994.

layover facilities. In 1997, the Metropolitan Bus Authority (MBA) implemented the system restructuring, which included reducing the number of routes from 43 to 29, including both trunk and feeder routes. These improvements led to an increase of 24% in ridership during first year[2]. The ongoing and future efforts to improve the current bus system are aimed to maintain ridership and to build a ridership base for the new mode of transportation for San Juan: Tren Urbano.

The públicos are also expected to provide feeder services for Tren Urbano. Públicos are a jitney system, which consist of privately-owned van-type vehicles that serve specific routes with a fixed fare, but with a low quality of service. The government regulates the fares and the routes; however, drivers provide the service at whatever times they want and with whichever vehicle they own (Lee, 2000). Frequently these vehicles are old and without air conditioning, and the drivers do not follow a specific timetable: vehicles depart when they are completely full, and operators pick up passenger along their routes, which leads to overcrowded vehicles as well as unreliable service. The Puerto Rico Highway and Transportation Authority (PRHTA or simply the Authority) is in the process of developing plans to create a licensing program in conjunction with the público association that would require públicos serving Tren Urbano stations to meet certain specifications regarding vehicle characteristics, fare collection, and operational guidelines[3]. Previous research at MIT and the University of Puerto Rico have studied different issues related to the integration of públicos with Tren Urbano; the reader is referred to González (1994), Lau (1997), Vargas (1999) and Lee (2000) for further information on this topic.

Tren Urbano (Figure 1-1) is a new rail system that will represent an alternative mode of public transportation in the San Juan Metropolitan Area. Tren Urbano Phase I is now under construction, and it is expected to become the 'backbone' of transit service in San Juan. This first phase consists of a 17-km long alignment with 16 stations in total from Bayamón to Santurce: moving west to east from Bayamón to Río Piedras, and then

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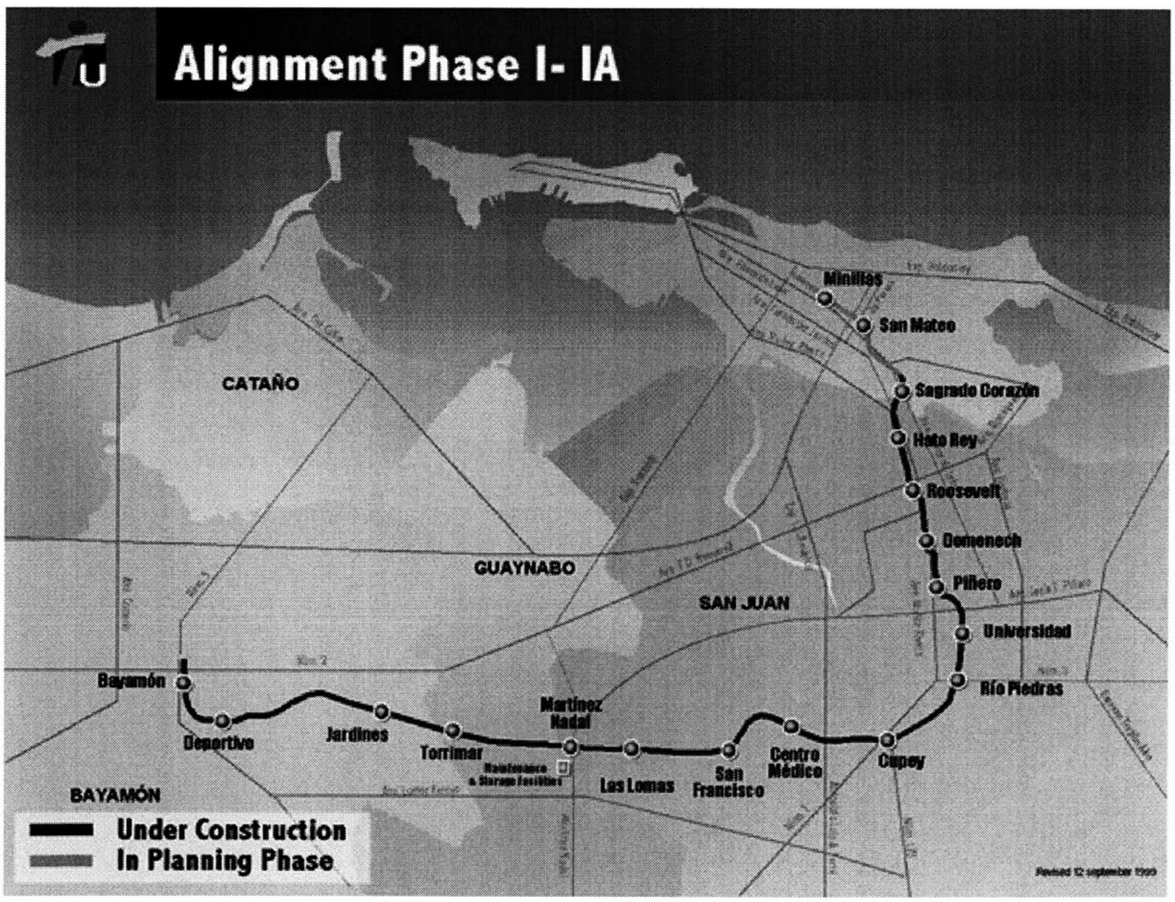
[2] Tren Urbano Office. *Tren Urbano Feeder System Report*. May 27, 1999.
[3] Ibid.

north to Santurce. As mentioned above, buses and públicos are expected to be important feeder services for this new mode. Phase IA is expected to be the first extension beyond Phase I, and consists of two additional stations in a 1.6-km long alignment moving from Sagrado Corazón station to the Minillas area in Santurce. The Tren Urbano goals, as stated in the FEIS, are (1) to improve mobility in SJMA, (2) to expand public transit service capacity, (3) to improve transit service efficiency, convenience and reliability, (4) to minimize the impacts on environment, (5) to support SJMA economic growth, and (6) to design, construct and operate the system in an efficient and effective manner.

Figure 1-1: Tren Urbano Alignment - Phases I and IA



The system's operation and maintenance (O&M) were included in one of the seven contracts into which the construction was divided. This is the first case in the United States where a publicly-owned rapid transit system is to be privately operated under contract. The Authority recognized the lack of local expertise in operating a rail system, and the importance of providing a high quality service that will satisfy the needs for improved public transit in the SJMA. The Authority designed an O&M contract that stressed technology transfer so as to create a cadre of local expertise that will be part of the SJMA workforce[4]. The contractor is responsible for the administration and management of the system, daily operations, system and vehicle maintenance, fare collection, security, and technology transfer. The operating contract period is five years after opening with the option to continue operating the system for five more years.

To ensure high service quality, the contract includes financial incentives and penalties for O&M. These incentives and penalties include on time performance, station cleanliness, vehicle maintenance and cleanliness, facilities maintenance, ridership and reports accuracy. Chapter 3 discusses the Tren Urbano O&M contract in more detail.

No existing North American Transit Agency has a structure of incentives and penalties for operations and maintenance of rail transit, given that the owners directly operate these transit systems. Hence, Tren Urbano is the first case in the United States where a rail transit system will be operating under contract. This places Tren Urbano in a challenging position; the transit industry 'eyes' will be observing the success or failure of Tren Urbano operations as an example of how private contracting can work on a rail system.

1.2 Motivation and Problem Statement

Certain bus routes, commuter services and paratransit are examples of privately contracted services in the United States public transportation industry. According to Halvorsen (1993), the involvement of the private sector to operate transit systems is aimed at reducing the public cost of transit and/or increasing its effectiveness. Table 1-1

[4] Puerto Rico Highway and Transportation Authority. *Final Environmental Impact Statement.* November 1995.

summarizes the amount of contracting services for the public transportation sector in the United States. As mentioned above and from the APTA data in Table 1-1, no rapid transit is privately contracted. Table 1-1 shows an increase in the use of privately contracted services in the last 10 years; this increase is primarily reflected as an increase in purchased transportation for bus, vanpool, and ferry systems.

In public transit service contracts, incentives and penalties are typically used to encourage the private sector to provide high levels of service quality. Given the existence of these contract terms, the contractor will try to maximize the net income from the operation by maximizing incentive revenues (as long as these amounts exceed the cost of meeting the standards) and minimizing penalties. Ideally the contract terms should seek to align the financial interests of the operator with the objectives of the owner and the interests of the passengers. However, if the penalties and incentives are not well structured we may encounter situations in which appropriate actions to maximize service quality are in conflict with the contractor's financial interests. One example of a situation in which actions to assure high quality service might be in conflict with contractor's financial interest is during and immediately after a disruption in service.

All rail systems are subject to occasional disruptions, which can be divided into major and minor disruptions. Minor disruptions can be further divided into routine and non-routine disruptions. In the case of major disruptions, pre-planned strategies such as the operation of substitute bus service might be required to minimize the disruption impact on service quality. With routine and non-routine disturbances different approaches to minimize the effects on service quality may be taken depending on the capabilities and characteristics of the system as well as the type of disturbance. For example, during a routine disturbance in a system without train regulation capabilities the controller may implement various control strategies to improve service. However, in systems with automatic train regulation capabilities, the trains performance may be adjusted and this may be adequate. A non-routine disruption requires the intervention of the controller and the use of specific control strategies to minimize the impacts on service quality. The disruption classification will be discussed in more detail in Chapter 2.

Table 1-1 Purchased Transportation as a Share of Transit Operating Expenses

Mode	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998[5]
All Modes	5.1%	5.6%	6.0%	9.9%	9.6%	10.4%	10.9%	10.8%	11.8%	11.6%	10.1%
Motor Bus	3.9%	4.2%	4.5%	-	-	-	-	-	7.1%	6.5%	8.2%
Rapid Rail	0.0%	0.0%	0.0%	-	-	-	-	-	0.0%	0.0%	0.0%
Ferry Boat	2.8%	14.4%	NA	-	-	-	-	-	4.7%	5.8%	27.6%
Commuter Rail	9.5%	8.8%	12.3%	-	-	-	-	-	13.7%	12.2%	7.2%
Vanpool	9.3%	0.8%	NA	-	-	-	-	-	25.8%	21.3%	29.6%
Demand Response	59.7%	55.4%	58.6%	-	-	-	-	-	57.9%	55.1%	61.5%

Sources: (1) Halvorsen, Rick D. *Economic Efficiency in Transit Service Contracts: The Role of Contract Structure.* Master Thesis, June 1993; (2) American Public Transit Association. *Transit Fact Book.* 1998 & 1999; (3) www.apta.com

[5] 1998 figures represent preliminary data, final numbers will be available by March 2001 (www.apta.com)

In the Tren Urbano case for a routine disruption the control system is designed to keep the system running on-schedule automatically. In this case, there should be little, if any conflict between the performance incentives and the public interests. However, as mentioned above, when a non-routine disruption occurs, the controller needs to take corrective actions in order to minimize its impact. These actions may include the application of train control strategies such as holding, short-turning, expressing and deadheading. The main purpose of these control strategies is to reduce the impact of a disruption on service quality by reducing waiting times and returning to normal operation as quickly as possible. In the case of Tren Urbano, when the controller make a control decision, it is logical that he will try to minimize the financial impact of a disruption given the contract incentive and penalty structure. If the contract terms are not optimally specified, minimizing the financial impact of a disruption might not necessarily lead to control strategies that optimize service quality to passengers.

1.3 Objectives

The specific objectives of this research are:

1. To study the control strategies which might be appropriate (holding, expressing, deadheading and short turning) in the event of occasional minor service disruptions affecting Tren Urbano Operations.
2. To assess the likely effects of contract terms on service control during recovery from disruptions and compare the implied strategies with those strategies that could provide best possible service quality at these times.
3. To understand how the Tren Urbano Control System operates and to assess its effectiveness during and after disruptions.
4. To recommend any changes in contract terms which may be desirable to ensure providing best possible service quality during recovery from disruptions.
5. To propose the set of effective control strategies which may be most effective in maintaining good service quality during recovery from disruptions.

1.4 Methodology

The research approach to the problem under study is divided into four major tasks. The first task is a preliminary analysis of the existing contract terms. Each clause will be carefully examined to identify and assess any potential problem areas. A new structure will be recommended based on this critical assessment.

The second task involves comparing the optimal selection of control strategies (such as short turning and holding) with the controller's likely selection of strategies based on the incentives and penalties established in the contract. For this purpose, an optimization model will be used to develop the optimal set of control strategies. Shen (2000) developed this optimization model as part of his thesis research. In the analysis presented in this thesis, the model was used to determine control strategies immediately around the disruption location. The objective function minimizes the on-board delay plus the on-platform waiting time during a disruption. The hypothetical Tren Urbano controller decisions will also be evaluated using this model. Contract terms will be included as constraints in the model to assess the impact of the contract in the selection of strategies. A second method will be used to estimate the impacts of the contract in the control decisions. It consists in a set of equations that estimates the impacts of a disruption looking not only at the control strategies to minimize the headway variance, but also the dispatching decisions at the terminal as one of the elements to minimize the disruption impact on service quality. These equations include on-board delay, which is divided into passive and active holding, plus on-platform waiting time and additional waiting time for passengers left behind. The input required for the second method consists of the headway sequence at every station, which is obtained from Shen's model result and from the dispatching decisions at the terminal. These dispatching decisions at the terminal include the use of the minimum recovery time for trains behind the blockage and holding trains ahead of the blockage. The methods mentioned here will be described in more detail in Chapter 4.

The third task consists of an assessment the Tren Urbano Control System. As mentioned above, the Tren Urbano Control System is designed to deal with routine disruptions and to maintain on time performance. However, during a service disruption, it may be necessary for manual intervention by the controller to minimize the impact of the disruption along the line. The interaction of the control system and manual decisions during a disruption will be studied to identify areas of ineffectiveness, if any, on how the control system behaves during a disruption. The assessment of the Tren Urbano control system will be used to determine how the system capabilities can be used in order to obtain the maximum benefits. The resulting findings will be integrated into the proposed changes in contract terms.

The fourth task consists of integrating the results of the previous three tasks to propose a new structure for the Tren Urbano on time performance contract terms. In some cases, various alternatives will be developed to address a particular problem in the current contract. The advantages and disadvantages of each alternative will be analyzed and a preferred alternative identified.

1.5 Literature Review

The literature review is divided into two major categories: On-time Performance measures and Operations Control Strategies. The first category is used to form a foundation on which to make an initial assessment of the contract terms, and to recommend restructuring if appropriate based on current practice. The latter serves as the base for development of control strategies to be used during recovery from disruptions.

1.5.1 On time performance measures

On time performance is one of the most common concepts used by transit agencies to assess reliability and service quality. It is commonly defined as a percentage of trips that are "on-time". Typically, an on time trip is defined by its schedule adherence, where on-time means that it should arrive at a point between X minutes early and Y minutes late compared with its scheduled arrival time at that point. In the case of high frequency systems, on-time performance is often represented by headway regularity rather than schedule adherence. A trip can be defined as on time in a high frequency system if its headway is within some range of the scheduled headway. On high frequency systems, passengers are interested in a vehicle arriving soon rather than boarding a specific trip; they do not rely on a timetable to plan their trips (Welding, 1957). However, in low frequency systems, passengers time their arrivals to minimize their waiting time at a particular location.

Welding (1957) in an early attempt to explain instability of public transportation services mentions that in the case of infrequent service a timetable is provided to transit riders, and that such systems should "run to the published timetable"[6]. On the other hand, he also mentions that for frequent services, users do not time their arrivals to board a given trip. Rather, they arrive randomly in order to board the next train or bus, which is expected to arrive within a certain interval of time (or headway). The distinction between measuring on-time performance for high and low frequency systems is mentioned in almost all literature in which reliability and service quality measures are discussed.

Marx (1988) reported performance standards for eleven privately contracted transit systems. The performance standards included incentives and penalties developed by each transit agency in order to assure high service quality. From the eleven systems reported, nine included on-time performance incentive/penalty clauses in the contract. These nine systems included three paratransit services with the remaining being fixed route bus systems. In general, the on-time performance window for the bus systems range from one-minute early to five minutes late with only one system allowing buses to arrive 8-minutes late and still be "on-time". The structure of the incentives and penalties varied among systems, given that they were designed for each individual system.

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[6] Welding, P.I. The Instability of a Close Interval Service. *Operational Research Quarterly* Vol. 8 No. 3 1957. pp 133-148

Wilson et al (1992) developed a system to monitor service quality on high-frequency rail systems, focusing on the Massachusetts Bay Transportation Authority (MBTA). The three measures of service quality used in this monitoring system are: (1) expected passenger waiting times, (2) difference between actual and ideal service quality, and (3) the percentages of passengers who receive good and bad service. The paper is based on the objective of minimizing passenger waiting times rather than minimizing the difference between the scheduled and the actual train arrival times (on-time performance). On-time performance based on schedule is an appropriate measure for low-frequency systems, where passengers try to arrive to a station just before the vehicle scheduled arrival.

Given that passenger waiting-time is a function of the headway, minimizing the variance in headway minimizes the passenger waiting time. The equation that describes the expected waiting time for a high frequency system is as follows:

$$E(WT) = \frac{H_{mean}}{2} * (1 + \text{cov}^2 H) \qquad (1\text{-}1)$$

where

$E(WT)$	=	expected passenger waiting time
H_{mean}	=	average headway
$cov\,H$	=	the square of coefficient of variation of headway, defined as the $\frac{Variance\ H}{H^2_{mean}}$

Equation (1-1) is the base of the analytical methodology developed in Chapter 4 to estimate the disruption impacts to service quality, and represents the basic rationale for headway variance minimization in order to minimize the passenger waiting time during a disruption.

Halvorsen (1993) studied the importance of contract structure for privately contracted transit services by exploring how it affects the benefits received by the society (transit agency and users) and the contractor. To analyze contract structure he undertook three major tasks: (1) a review of contract economics, (2) a survey to transit agencies about their contract practices, and (3) an analysis of three case studies of transit agency services that are privately contracted. He developed guidelines for transit service contracting including general recommendations on how to structure incentives and penalties given the impact they have depending of the contract type and the contractor's reaction to their enforcement.

A study by MacDorman & Associates and Wilson (1995) presents service quality measures and standards used by major North American transit systems, including bus, light rail, rapid rail and commuter rail. In general, as would be expected, rail systems base on-time performance on headway adherence rather than schedule adherence.

Strathman et al (1999) presents the first phase of a three-phase project to analyze the benefits of deploying a computer-aided dispatching system for the Tri-Met bus transit system in Portland, Oregon. The first phase consisted of collecting baseline data to assess the system's reliability prior to the implementation of the dispatching system. Four measures were used to estimate reliability: on-time performance, headway ratio (HR), run time ratio (RTR), coefficient of variation of HR, and excess waiting time (EW). HR is the alternative measure that estimates headway adherence, rather than schedule adherence. HR is defined as the ratio of observed headway to scheduled headway. The need to estimate HR reflects the importance that high frequency systems' users give to headway adherence. According to the authors, the reason to include on-time performance as a measure of reliability was "recognizing its wide-spread use in the transit industry"[7].

[7] Strathman, James G. et al. Automated Bus Dispatching Operations Control, and Service Reliability. *Transportation Research Record 1666.* TRB, National Research Council, Washington, DC, 1999.

1.5.2 Operations Control Strategies

For the purpose of this research, the four most recent studies from MIT related to real-time operations control strategies were reviewed: Eberlein (1995), O'Dell (1997), Song (1998), and Shen (2000).

Eberlein (1995) studied holding, expressing and deadheading, independently and in combination to improve system performance when faced with routine disturbances. In her work, two types of systems were studied: a general 'G' and a fixed 'F' system. System 'G' represents the case in which "passenger demand varies across stations and vehicle dwell times depend on both passenger boardings and alightings"[8]. System 'F' is a simplification of 'G', which assumes "constant passenger rates across stations and fixed dwell time"[9] so that analytical results can be obtained. In the case of system G, she combined analytical and empirical methods, and developed algorithms to obtain optimal control strategies. Sensitivity analysis was performed in order to test stochasticity in parameters assumed deterministic, such as interstation travel times and arrival rates.

The Massachusetts Bay Transportation Authority (MBTA) was the case study used to test these models. She tested the models using the Green Line, which is a light rail system in the Boston metropolitan region, which consists of four branches. She analyzed data from the 'B' branch of this light rail system, which starts west of Boston at Boston College station moving east around 6-miles to downtown Boston. The Green Line does not have automatic train control; hence adjustments to deal with routine disturbances must be through the use of control strategies. The results of this research showed that the combination of strategies was the most effective approach to control, although the marginal benefits of combining strategies are limited. Holding alone was the best control strategy when compared to both deadheading and expressing alone and if used continuously, it could reduce headway variance. She concludes that the

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[8] Eberlein, Xu Jun. *Real Time Control Strategies in Transit Operations: Models and Analysis*. Ph.D. dissertation. June 1995.

[9] Ibid.

combination of holding and expressing/deadheading is more effective when holding is restricted by schedule constraints. Another important conclusion of this research is that frequent control actions are key to obtaining the maximum effectiveness from control strategies.

O'Dell (1997) studied the use of holding and short turning in the case of non-routine system disruptions in order to minimize the impact on passenger waiting times. She studied different holding formulations and the combination of holding with short turning and used fixed and general system models similar to Eberlein's work. The results showed that the application of optimal control strategies can result in significant waiting time savings in non-routine disruptions. She tested these models on the MBTA Red Line, which is a rail transit system starting in Cambridge, passing through downtown Boston and then dividing into two southern branches: Ashmont and Braintree. The passenger waiting time savings observed ranged from 15% to 50% compared with the "no control" case. The research also showed that most of the benefits could be obtained by controlling a small set of trains ahead of the blockage, because the contribution of controlling trains behind the blockage to reducing the passenger waiting time is not significant.

Song (1998) studied the use of holding and short-turning to deal with the terminal dispatching problem. The dispatching problem occurs when trains are not expected to arrive at the terminal early enough to be dispatched as scheduled for the next trip. Eberlein mentions that dispatching headway randomness is one of the major factors contributing to irregular headways. However, in her formulation it was considered to be deterministic given that dispatching depends on the availability of vehicles. Song developed a heuristic dispatching control model to deal with the dispatching problem. The MBTA Red Line was used to test the effectiveness of the model, and the results showed savings up to 14% in passenger waiting time compared with the "no control" case.

The most recent MIT work on real-time control strategies is Shen's (2000) model. The deterministic model developed tests holding alone and in combination with short turning and expressing. The objective function is to minimize the total on-platform passenger waiting time plus the on-board delay. As in the previous research by O'Dell on which Shen's model is strongly based, the MBTA Red Line was used to test the model. The results showed that holding and short-turning reduced waiting time by 10-60%, when compared with the 'no control' case and that incremental expressing benefits are modest compared to the benefits achieved by the other two strategies. Shen's model is used to estimate the optimal control strategies for the disruptions analyzed in this thesis.

Since the model assumed deterministic disruption duration, Shen used a sensitivity analysis to estimate the impacts of errors in the disruption time estimate. This analysis showed that holding and expressing strategies are fairly robust; however, short turning can be quite sensitive to the accuracy of the disruption duration estimate.

1.6 Thesis Content

The remainder of this thesis is organized as follows. Chapter 2 describes the optimal control strategies in the case of major disruptions based on previous research. The model that will be used subsequently in the evaluation of various scenarios is introduced here. Chapter 3 defines, describes and criticizes the contract terms in the Tren Urbano O&M contract related to on-time performance. The contract terms are analyzed and potential problems that might arise given the existing structure are presented. Then, we propose an initial restructuring of the contract based on more realistic on-time performance objectives. Chapter 4 presents the evaluation of the optimal control strategies model introduced in Chapter 2. The model is modified to represent the contract term clauses that restrict control actions given the incentive/penalty structure. Two disruption locations and two disruption durations are analyzed to assess the impact of the contract terms on control strategies versus the optimal solution. An analytical model is introduced to include the effect of dispatching decisions at the terminal, which depend on either one of two objectives: (1) minimizing headway variation for the optimal solution, or (2) minimizing the number of late trips for the hypothetical Tren Urbano solution. Chapter 5 describes the Tren Urbano control system capabilities as they would affect recovery from a routine disruption and how the system operates during a non-routine disruption. Chapter 6 presents the final recommendations on contract restructuring. Finally Chapter 7 summarizes the research findings and results, and provides some recommendations on future research.

Chapter 2:

Control Strategies and Disruption Analysis

During any disruption, the normal operation of a rail system is affected. Consequently, service quality is affected through increases in passenger waiting times in stations, in-vehicle delays and overcrowded trains. The system controller makes control decisions in real time (starting immediately after the disruption occurs) in order to minimize the negative impacts of the disruption. If disruptions are not dealt with effectively, service quality will be affected, and consequently also ridership.

According to Song (1998), disruptions can be classified into two categories: major and minor disruptions. Major disruptions are those that cause a delay of more than 20 minutes. The best way to deal with this kind of disruption is to have pre-planned strategies, given the length of such a disruption. Some of these pre-planned strategies include single-track operation, and providing buses to transport passengers between stations. The strategies would depend on the magnitude of the incident, whether or not one track is available to provide service, the number and location of stations affected by the incident, time of day, cause of disruption, etc. For example, assuming that trains can not travel between Centro Médico station and Universidad station, a potential solution could be to provide buses that would transport passengers between Centro Médico and Universidad in both directions, stopping at the stations within that segment. The number of buses required would depend on the demand patterns corresponding to the particular time of day at which the disruption occurred, running time, traffic conditions and operators' availability, among others.

Minor disruptions are those causing a delay of less than (about) 20 minutes. Minor disruptions could be further distinguished between routine and non-routine disturbances. An example of a routine disturbance is heavy boardings and alightings at a station. For a routine disturbance, real time operations' monitoring tracks the system performance. If the system does not maintain on time performance, the control system may automatically take corrective actions, such as modifying train speed and station dwell times that will reduce passenger waiting time and maintain transit system performance. For systems without this kind of technology, control strategies are used to maintain the regular operation of the system. As Eberlein (1995) mentioned in her thesis, frequent control actions are needed to obtain the maximum effectiveness during routine operation of the system.

A non-routine disturbance includes, for example, a disabled train, a power failure, or a medical emergency. In this case, control strategies can be used effectively to deal with the disruption, given the availability of real time information accessible at the Operations Control Center (OCC). Control strategies are used because the system capability to recover from disturbances is not enough to reduce the impact of the disruption to acceptable levels. System performance degradation is the outcome of not dealing immediately with the disruption, and the result is long headways that keep increasing further along the line, and the bunching of vehicles. The impact will also extend well after the disruption is cleared. Control strategies are selected in order to minimize the impact of the disruption and optimize the system's performance. For the purpose of this research, we will focus on non-routine disturbances, since Tren Urbano will employ a sophisticated control system incorporating an Automatic Train Regulation (ATR) system that helps the system to maintain the desired performance during routine disturbances. Non-routine disturbances represent the main factor that will affect on time performance.

This chapter describes control strategies commonly used in rail systems during and immediately after non-routine disruptions and will describe their impacts in improving service quality. Then, the most recent model developed to identify the optimal set of control strategies for a given disruption is presented. This model will be the base used to evaluate the impact of the contract terms of Tren Urbano's Operations and Maintenance contract during a disruption. As mentioned before, the model will be used to identify the control strategies that will minimize the disruption impact. In this chapter the original form of this model will be presented. Chapter 4 presents the modifications made in order to represent Tren Urbano contract terms in the hypothetical Tren Urbano strategy.

2.1 Control Strategies

As mentioned above, when a non-routine disturbance occurs in a rail system, the controller makes control decisions in order to minimize the impact on service quality. As a result of the incident, the passengers are subject to longer waiting times and overcrowded trains. These factors degrade service quality, and consequently cause impacts on ridership. Transit systems use control strategies in order to provide the best service quality possible during and immediately after a disruption. These strategies include holding, expressing, deadheading, and short turning.

To determine the optimal set of control strategies, we are interested in minimizing the impact of the disruption on service quality. During a disruption, passengers are concerned about security, safety, and how long the disruption will take to be resolved, among other issues. In addition to considerations of which strategies to use to minimize the impact on riders, the controller must keep passengers informed of the system status, especially in the case that passengers are on board a vehicle that will be controlled as part of the recovery strategies. Also, in the case of holding, the holding location for any train should be at a station, avoiding inter-station stopping, since passengers perception of security might be negatively affected by being stuck on a train between stations.

Service quality can be measured in several different ways, including measures such as passenger waiting time (WT), number of crowded trains, number of affected passengers, number of passengers left at a station, and number of complaints. Some of these measures are easy to obtain given the availability of real-time monitoring and automatic collection of data. For Tren Urbano, we decided that the set of strategies chosen is the one that minimizes passenger waiting time given that it is a measure commonly found in previous research related to disruption analysis and control strategies. Passengers are very sensitive to waiting time (Abkowitz et al, 1978). Moreover, passenger waiting time is one of the easiest measures to estimate, given that it basically depends of the demand characteristics of the system, the headway sequence of trains at the stations, and other operational characteristics (dwell time and minimum headway).

Passenger waiting time includes both on-platform waiting time and on-board delay. On-platform waiting time refers to the amount of time passengers have to wait for the next train to arrive. The maximum on-platform waiting time for a specific group of passengers arriving at a specific station is measured from the departure of a train to the arrival of the next train plus its dwell time. The on-platform waiting time should include the passengers that are able to board the train as well as the passengers left behind due to capacity constraints. The additional on-platform waiting time for passengers left due to overcrowding is estimated as the time between the departure of the train and the departure of the next train.

On-board delay is the amount of time that passengers have to wait inside the train due to holding. There are two types of holding during a disruption: passive and active holding. Passive holding corresponds to the required holding experienced by trains behind the blockage, which are held at a station until the blockage is cleared. Active holding applies to those trains ahead of the blockage which are held as part of the control strategies selected by the controller. Holding is measured as the time between the end of a train's dwell time and the departure of the same train. According to previous research, passengers may perceive waiting inside the train during holding as less onerous than platform waiting time. A weighting factor for on-board delay is included when estimating total passenger waiting time to account for this. The passengers affected by holding include the passengers that board the train during the dwell time at the station plus the passengers that arrive during holding. However, passengers that arrive during holding have zero on-platform waiting time because they are able to board the train while holding and the only waiting they experience is the on-board delay.

The control strategies description presented here is based on prior research by Eberlein (1995), O'Dell (1997) and Shen (2000). Eberlein studied the use of control strategies to deal with routine disturbances, and considered the use of holding, expressing and deadheading alone and in combination. O'Dell and Shen analyzed non-routine disruptions. O'Dell analyzed the use of holding and short turning to deal with disruptions of 10 and 20 minutes, and developed an optimization model that minimized on-platform waiting time only. Shen's work is an extension of O'Dell's research. In addition to including on-board delay in the formulation, he also included expressing trains as a control strategy. For the purpose of this analysis, Shen's model will be used to determine the optimal strategy during disruption in Tren Urbano because, first, it includes both on-board and on-platform waiting time and, second, it is the most recent complete approach to developing optimal control strategies.

2.1.1 Holding

In high frequency transit services, where the mean passenger arrival rate is assumed constant and passenger arrivals are random, the expected passenger waiting time is described by equation (1-1). If there is no variation in headways, the coefficient of variation is zero, and as a result the expected waiting time, E(WT), is half the headway. As the headway variance increases, E(WT) also increases. For example, let us assume two different headway sequences with the same H_{mean}, 6-6 minutes and 5-7 minutes. The first sequence has zero variance; therefore the E(WT) is simply half the mean headway, which is 3 minutes. On the other hand, the variance for the second sequence is 2, and E(WT) = 3*(1+2/36) = 3.2 minutes. This represent a 5.6% increase when compared to the first headway sequence. If the headway sequence was 4-8 minutes, the variance is 8, and the E(WT) = 3*(1+8/36) = 3.7 minutes. In this case, the expected waiting time increases by 22% when compared with the 6-6 minutes headway sequence. Minimizing headway variance is desirable in order to reduce the E(WT). In order to even out headways, holding is one of the easiest control strategies that can be applied.

Holding consists of delaying a train in a station, usually when there is a short preceding headway and a long following headway, to reduce headway variance[10]. To obtain the maximum benefit of holding, trains are held at the station with doors open to allow people to board (or leave) the train. People that board during holding have zero on-platform waiting time given that they are able to board the train as soon as they arrive at the station. Since no station is skipped, it is less frustrating to passengers. Stations with high arrival rates are reasonable locations for holding trains, given that more passengers benefit because they can board the train and with no on-platform waiting time. After a train passes heavy boarding stations, it should not be held because there may not be a large enough number of passengers that could benefit from holding, and the increase to on-board waiting time may be greater than the reduction to on-platform waiting time. Also, if there are a considerable number of boardings at stations after the holding station, the waiting time to passengers at later stations is reduced and it is more likely that the passenger waiting time reduction will be greater than the on-board delay increase due to holding.

Another characteristic that is desirable in this case is a relatively small normal passenger load (without holding) at the holding station, because as a result of holding the travel time for these passengers is increased. Holding is also more preferable at a station than between stations, given that passengers may perceive inter-station holding to be a problem with the system and then may raise anxiety. Finally, an important consideration is to avoid holding trains so long that the acceptable crowding levels for the train are likely to be exceeded at subsequent stations. Holding is expected to improve the level of service after a disruption. Therefore, if trains are held in front of the blockage, they are expected to reduce the impact of a disruption and not to jeopardize the service to

[10] Wilson, Nigel H.M., R.A. Macchi, R.E. Fellows, A.A. Deckoff. *Improving Service on the MBTA Green Line through Better Operations Control.* Transportation Research Record 1361. 1992, pp. 296-304.

passengers arriving at locations before the blockage by leaving passengers at stations due to overcrowded trains.

Eberlein studied holding as a routine control strategy on a rail system. In her analysis, she did not include the on-board delay due to holding which means that control benefits were overestimated. For the holding only analysis her findings were:

1. Holding is independent of demand pattern; it depends mainly on the headway pattern. This property is derived from the analysis Eberlein made for the dispatching headway effect. She found that if for train *i* the dispatching headway is smaller than the minimal headway of its preceding train, *i-1*, the headway of train *i* will decrease monotonically over the trip. In the opposite case, if the headway of *i* is larger than the maximum headway of *i-1*, the headway of *i* will increase over the trip. When the dispatching headway of *i* is between the maximum and minimum headway of *i-1*, the headway variance along the route will be small.
2. Holding is the single most effective strategy when compared with benefits obtained with either deadheading or expressing, and if used continuously, decreases considerably the headway variance and the need for station skipping control strategies.
3. The best station at which to hold trains is the first station in a direction (terminal), which gives important insight into the dispatching problem. Small initial headway variability caused by the irregularities in dispatching can increase significantly along the line resulting in bunching and larger preceding headways, as shown in the dispatching headway effect analysis.
4. The savings from holding obtained by the analysis with the MBTA Green Line data resulted in 31% passenger waiting time savings for the case without a terminal schedule constraint, and 20% with the constraint.

In the case of Tren Urbano, dispatching strategies can be used to minimize the headway variance, given the availability of recovery time at terminals. The effects of bunching and large preceding headways are not principal reasons to consider dispatching headway regularity in this research, because dwell time for Tren Urbano has been assumed as a fixed value during the design process. In fact, dwell times are a function of boardings and alightings, and headway irregularity affects the dwell function resulting in bunching and increased headway variability. If the preceding headway is large, when a train arrives at a station dwell time will increase, and consequently, the headway increases even more. The opposite effect occurs with a short preceding headway; dwell time is reduced, and consequently, headway is also reduced.

O'Dell and Shen both studied holding in the case of disruptions on the line. The main differences between their formulations are that Shen included in the formulation the on-board delay caused by holding and station skipping strategies. Holding benefits largely accrue from holding trains ahead of blockage. Even though as the controlled set of trains is increased the benefits from holding increase, the marginal increase of holding an additional train is small after several trains are already being held. Figure 2-1 present the results O'Dell obtained from varying the set of trains held ahead of the blockage. The results indicate that "the time savings for (holding) two and for four trains are approximately 75% to 90% of the savings for (holding) eight trains"[11].

O'Dell showed that active holding for trains behind the blockage does not provide any significant benefit, and Shen concluded that holding trains behind the blockage should be strictly to maintain the minimum safe separation between trains. From O'Dell's disruption analysis, the savings from holding trains behind the blockage were less than 5% when comparing passenger WT behind the blockage in the do-nothing case versus the holding strategy.

In summary, in addition to being the simplest control strategy in terms of application because it is the least disruptive, holding benefits include the reduction to passenger waiting times due to a reduction in headway variance at stations after the holding point. Also, passengers arriving during holding can board the train immediately,

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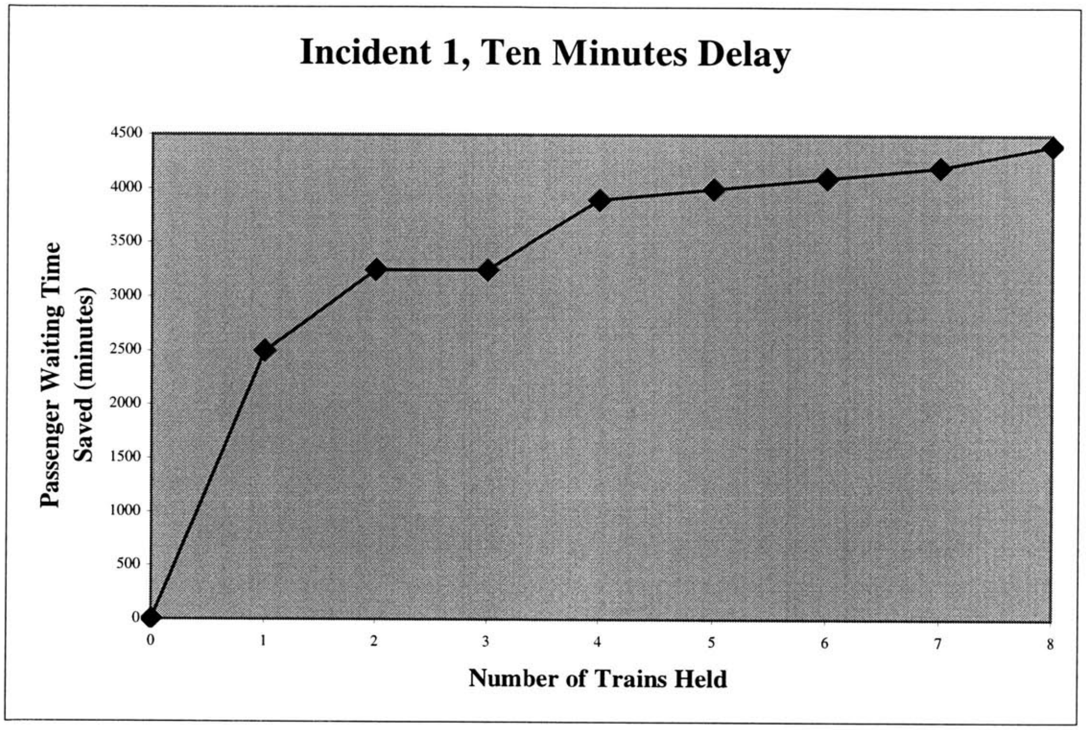
[11] O'Dell Susan W. *Optimal Control Strategies for a Rail Transit Line.* Masters Thesis. June 1997.

which results in passengers with zero on-platform waiting time. The benefits from holding result mainly from holding trains ahead of the blockage; however, the number of trains to be held can range between 2-4 trains, given that a significant percentage of the waiting time reduction are obtained from holding a small number of trains.

Figure 2-1 Varying Impact Set Size



Source: O'Dell, Susan W. *Optimal Control Strategies for a Rail Transit Line*. June 1997, pp. 69

2.1.2 Short-turning

Short turning consists of changing the travel direction of a train in order to reduce the gap created by a disruption. It is the second most effective method of control, and when used in combination with holding can provide greater benefits than holding alone. Short turning is restricted by the location of crossover tracks and its effectiveness is very sensitive to the amount of time required to turn a train. Short turning should be used only during non-routine disruptions since it is too disruptive for routine control. Routine disturbances, as mentioned earlier, are the consequence of, for example, heavy loading, which certainly result in gaps of far less than 10 minutes. O'Dell and Shen assumed a deterministic short turning time that averages 6 minutes from the arrival of the train at the crossover tracks to the departure in the opposite travel direction. This value does not include the time required to unload the train at the station and the arrival at the first station served in the reverse direction. Therefore, in a routine disturbance, short turning might require holding trains behind the short turn point in the reverse direction, causing an increase in on board delay. In addition, it inconveniences passengers in the original travel direction, which could not be justified by the benefits obtained from short turning.

The passengers benefited by short turning are those travelling in the reverse direction boarding after the short turn point, given that their waiting time is reduced compared to the 'do-nothing' option. However, according to Wilson et al (1992), there are three groups of passengers, that are negatively affected by short turning a train. The first group consists of the passengers whose destination is beyond the short turning point since they have to alight from the train and wait for the next train to arrive to complete their journey. Second are those passengers waiting to board the short turned train at the station before the short turning point, who have to wait for the next train. Finally, the third group consists of the passengers waiting at the skipped segment, whose waiting time is increased given the increase in headway caused by the short turned train.

The ideal scenario for short turning is to short turn a train close to the end of the route, having a low passenger load before short turning, and heavy passenger flows in the reverse direction. In this case, the number of passengers who benefit will exceed the number of affected passengers. However, during actual operations, the feasibility of short turning will depend on the locations of both the disruption and crossover tracks. In addition, the location of potential short turning candidates is very important. For example, suppose when a disruption occurs, a train has just passed the crossover location, and the next train will arrive at that point only in 4 minutes. It may take more than 10 minutes to move from the location at the moment of the disruption to the first station it arrives in the opposite direction; if the disruption is not long, it might interfere with the movement of the trains behind the short turn point. Short turning requires a length of time given that first the train has to be unloaded and then switch directions using the crossover tracks. The reversing action is done at a lower speed and the driver has to switch ends to reverse the direction of movement. Therefore, short turning is appropriate only when the disruption is significantly longer than the time required to short-turn the train.

Previous research has always included short turning in combination with holding. In O'Dell's thesis, the train which could be short turned and the short-turning location were both predetermined. The formulations for short turning considered the location of the disruption. If the disruption occurs at the beginning of the alignment, the best solution is to short turn trains in front of the blockage. On the other hand, if the disruption occurs at a point near the terminal, the best solution is to short turn trains behind the blockage. The short turned trains are expected to serve the greatest number of station possible, and it is the basis for the short turning decision process.

Shen also included short turning in his formulation, but in this case, any train could be short-turned at any point; the decision depending on the minimization of the objective function. To include this decision in the model, the system is divided into segments with each segment starting and ending at a crossover location. To determine the potential predecessors of a train located in a segment, we consider the train ahead and the potential short-turning candidate(s).

Shen found that short turning combined with holding often achieved the highest passenger benefits. Holding is always included in the short turning formulation to achieve the optimal reduction in passenger waiting time by reducing the headway variance. However, short turning is also quite sensitive to the estimate of the disruption duration. For example, if the duration is less than assumed, the short turning decision may be fully committed before the time duration of the disruption is known and it might cause additional unnecessary delays to trains behind the short-turned train. In the opposite situation, where the assumed disruption duration is less than the actual duration, a potential short-turning candidate might already have passed the crossover location and thus the short turn option may be precluded.

2.1.3 Expressing and Deadheading

Expressing and deadheading are station skipping strategies that can be used to reduce a long preceding headway and/or to increase a short following headway, and to reduce running time. The difference between these strategies is that deadheading should start at the terminal station and no passengers are carried over the deadheading segment whereas expressing can start at any point on the route, and passengers traveling beyond the expressing segment do not have to alight. In the case of expressing, those passengers traveling to the skipped segment are notified that they have to alight from the train and transfer to another vehicle. This action requires a certain amount of time for notification plus additional dwell time to allow passengers to alight from the train; an amount of time that is saved in the case of deadheading, in addition to a decrease in confusion that may be caused by expressing. The passengers who benefit from such strategies are those boarding after the skipped segment, and, in the case of expressing only, those travelling beyond the skipped segment. The passengers that are negatively affected by these strategies are those that are travelling to the skipped segment and those waiting on the skipped segment.

Eberlein studied both control strategies independently for routine control. The deadheading problem "is to decide which vehicles should be deadheaded and how many stations should be skipped". In the case of expressing, the additional decision is at which station expressing should start. Trains could be expressed over at most one segment. The findings of this research are:

- Expressing and deadheading are more sensitive to demand patterns than is holding.
- Deadheading and expressing result in quite similar time savings.

- While deadheading is not suitable for a route starting with high demand stations, expressing is particularly effective when the initial station has high demand.
- Deadheading is often more effective in high headway variation situation because control actions are made earlier.

When combined with holding, Eberlein concludes that the effectiveness of holding can be increased, while holding decreases the frequency of station skipping strategies and, consequently, side effects, such as frustration, are minimized.

Shen also included expressing in his optimization formulation; however, he studied it first in combination with holding, and finally combined it with short turning. The results showed that expressing provided only modest additional benefits.

2.2 Model Description

As mentioned above, to study optimal control decisions vs. Tren Urbano control decisions, we will use Shen's model. From the model, we will obtain both the optimal control strategy and the hypothetical Tren Urbano control strategy for a given disruption (refer to Chapter 4 for more details on the scenarios and the methodology). The model to be used will include only short turning and holding. Station skipping strategies will not be included in the analysis given that Tren Urbano control decisions are unlikely to use these strategies given the structure of the contract terms, as will be discussed in Chapter 3. In this section, the model will be described briefly. For a detailed description of the model formulation, assumptions, contraints and variables refer to Shen (2000). The variables, model and constraints are also presented briefly in Appendix A.

The objective of this model is to minimize the impact of a disruption. The two components of service quality included are the on-platform waiting time and on-board delay as expressed in the following equation:

$$Min \quad \sum_{i \in T} \sum_{m \in G} so_{i,m} \sum_{k \in m} \{ \frac{A_k}{2} * h_{i,k}^2 + p_{i,k} (d_{i+1,k} - d_{i,k}) + U^{iw} [\frac{A_k}{2} ht_{i,k}^2 + (l_{i,k} - A_k ht_{i,k}) ht_{i,k}] \} \tag{2-1}$$

where:

$d_{i,k}$ = Departure time for train i at station k

$h_{i,k}$ = Maximum platform waiting time for train i at station k

$ht_{i,k}$ = Holding time of train i at station k

$l_{i,k}$ = Passenger load on train i departing station k

$p_{i,k}$ = The number of passengers left behind by train i at station k

A_k = Passenger arrival rate at station k

U^{iw} = Weight for in-vehicle waiting time

$so_{i,m}$ = 1 if train i operates on segment m, 0 otherwise

The first two terms in the objective function are related to the on-platform waiting time. The first of these estimates the on-platform waiting time for the passengers that arrive at the station between the departure of the preceding train and the end of the dwell time for train i. The second term estimates the waiting time of passengers left behind by the preceding train. The final term in this equation estimates the on board delay. The on board delay component is divided into the passengers arriving during holding, and the passengers already on board when holding begins.

In order to be able to use a linear solver, the objective function must be simplified. After simplification of non-separable terms and quadratic functions, the objective function becomes:

$$Min \quad \sum_{i \in T} \sum_{m \in G} so_{i,m} \sum_{k \in m} \{ \frac{A_k}{2} * z_{i,k} + p_{i,k} (H_k + dw_k^0) + U^{iw} [\frac{A_k}{2} zt_{i,k} + l_k^0 ht_{i,k}] \} \tag{2-2}$$

where:

$z_{i,k}$ = Variable to approximate the quadratic term of platform waiting time for train i at station k

$zt_{i,k}$ = Variable to approximate the quadratic term of holding time for train i at station k

$l_{i,k}^{0}$ = Approximate passenger load for train i departing station k

dw_{k}^{0} = The typical dwell time at station k in that time period

The model will be used to assess which trains to hold and for how long, the headway sequences after short turning a train, and as a base to estimate the savings obtained from choosing the optimal solution versus the hypothetical Tren Urbano solution. The Tren Urbano solution is constrained by the contract terms, which are discussed in Chapter 3. Short turning is analyzed, but the location and the train to short turn is predetermined, in order to simplify the model formulation.

Chapter 3:

Tren Urbano Operating Performance Analysis

The transit industry is increasingly using private sector contractors to provide certain transit services. In particular private contractors are sometimes used to run certain fixed route bus, demand-responsive, and commuter rail services. This tendency is driven by the potential to reduce cost while improving service quality. However, the outcome of contracting private services depends heavily on the way the contract is designed and how the transit agency monitors performance and enforces the contract terms.

Incentives and penalties are frequently included in the contract to ensure the contractor pursues the goals established by the transit agency. The contractor's main interest in such a situation is to maximize their profit by both minimizing operation costs and maximizing income from the incentives terms in the contract. In a situation where it is inevitable that penalties will be imposed, the contractor will try to minimize the financial impacts. Designing the structure of contractual incentives and penalties is critical: the incentive and penalty terms should be structured in such a way that the contractor is motivated to comply with the performance standards covering the service quality provided to the riders.

Halvorsen (1993) studied "how the structure of contracts for the purchase of urban public transit services affects the benefits received by society and the contractor"[12].

[12] Halvorsen, Rick D. *Economic Efficiency in Transit Service Contracts: The Role of Contract Structure.* Master thesis. June 1993.

He developed a set of guidelines for designing the contract process as well as the service contract. These guidelines include some important considerations that could be applied in the development of incentives and penalties. These points are listed below and are used in the analysis of the incentives and penalties for Tren Urbano O&M contract.

1. Incentives and penalties will generally cause a greater increase in effort in a cost-plus contract than in a fixed fee contract. Also, in fixed fee contracts there may be a greater need for service quality and maintenance related provisions. The rationale for differentiating incentives and penalties for each type of contract is because in the case of cost-plus, the contractor is reimbursed for the total expenses (whenever it does not exceed the ceiling cost), and receives compensation for providing the service. Therefore, if meeting certain standards requires an additional effort that increases the costs of operation, the contractor will still receive their profit for providing the services and in addition are eligible to receive the incentive for meeting the standards. However, in a fixed fee contract, the payment received from the transit agency includes the operation expenses plus the profit. Hence, the contractor will try to reduce its costs in order to obtain the maximum profit, and his actions may affect service and maintenance of the system.
2. Incentives and penalties provide a risk of directing an excessive amount of effort and resources to these provisions and away from other important areas that are not subject to incentives and penalties. The size of the incentives and penalties should be large enough to encourage meeting certain specifications, but small enough to avoid such redirection of resources.
3. The transit agency needs to be clear about their objectives and to obtain good information on the objectives of the contractor in order to select the incentive/ penalty structure that will be most effective in achieving those objectives.
4. Incentives and penalties are only effective if the contractor understands how his actions affect the expected net benefits. Therefore, the contract provisions should be designed in such a way that the contractor's actions are reflected.

Halvorsen made a survey to study the types of contracts used for transit services. He observed that penalties and incentives were commonly used, and that penalties were used more frequently than incentives. However, incentives were enforced more frequently than penalties, because contractors naturally give notice when they meet the requirements for receiving a reward. In the case of penalty enforcement, the transit agency needs to collect the data required to prove that the penalty applies and to take the initiative of demanding the payment.

As mentioned previously, no rail transit system currently operating in the United States is privately contracted. Rail systems sometimes contract out support services such as station and vehicle cleaning; however, system operation is always the direct responsibility of the transit agency. Tren Urbano is expected to be a showcase of transit systems throughout the Americas; the Federal Transit Administration selected Tren Urbano as one of four demonstration projects because of the innovative procurement process selected for its implementation. Tren Urbano will also become a showcase for transit agencies worldwide that might be interested in contracting private firms to operate their urban rail systems.

This chapter is divided into five sections. First, the Operations and Maintenance (O&M) Contract for Tren Urbano is introduced. The second section presents the contract terms applying to on-time performance as they are stated in the O&M Contract. The third part analyzes the structure of the on-time performance clauses and assesses the potential problems that may arise with each contract term, based on both theory and practice. In the fourth section, on-time performance measures used in practice are described. Finally, an initial restructuring of Tren Urbano contract terms is proposed, based on the literature review of on-time performance measures.

3.1 Operation & Maintenance Contract

The Tren Urbano O&M contract is a fixed-fee contract. In a fixed-fee contract, the contractor receives a fixed fee for providing his services, profit included. The contractor has to control the cost in order to obtain the maximum profit. If the costs are too high, the contractor's profit is reduced and he might even suffer losses if costs exceed the fixed payment. According to the Tren Urbano O&M contract Section 4.2, the base compensation received by the contractor includes all costs, expenses, profit, overhead and other remuneration related to performance of services[13]. In the case of Tren Urbano, the contractor must submit an invoice every month including the fixed amount charged for O&M of the system, reimbursable taxes, the corresponding penalties and incentives, and the revenue credit. The revenue credit consists of the fare amount collected during that month. The fare revenues are part of the contractor payment for O&M, and are to be deducted from the total payment requested. Table 3-1 presents the base compensation for each year of operation.

Table 3-1 Annual Base Compensation Payment for Tren Urbano O&M

Year	Base Compensation
1	$27,360,927
2	$27,850,572
3	$29,499,215
4	$29,358,417
5	$29,776,122

This contract also establishes incentives and penalties to ensure high quality of service. The performance standards subject to incentives and/or penalties are:

- On-time performance
- Missed trips
- Fleet-wide mean distance between failures
- Vehicle preventive maintenance
- Facilities maintenance
- Train air conditioning

[13] Puerto Rico Highway and Transportation Authority, *Phase I of Tren Urbano: Systems and Test Track Turnkey Contract – Contract Book II Operations and Maintenance.* August 1995.

- Exterior cleaning of trains
- Daily interior cleaning of trains
- Heavy station cleaning
- Customer service response
- Cleaning adjustment to incentives due to compliance failure
- Reports submission
- Ridership incentive (not subject to penalty)

These performance standards have individual incentives and penalties subject to an annual maximum penalty of $1,500,000 and an annual maximum incentive of $1,250,000. The penalty is about 5% and the incentive is about 4.5% of the base compensation. These values seem reasonable in that they are high enough to encourage the contractor to provide good service quality.

The contract also includes a number of exceptions to the enforcement of the performance standards. If the Contractor does not meet a performance standard due to "a Force Majeure Event, actions of the Authority that cause delay or disruption in service, a power failure beyond the Contractor's control, water rationing by Puerto Rico public agencies, or an accident or incident caused solely by actions of Patrons or other third parties (including Patron illnesses not due to the fault or negligence of the Contractor, but not including Patrons temporarily blocking train doors in the process of entering or exiting trains), shall not be counted in determining offsets to Base Compensation, but shall be counted for purposes of calculating incentives to which the Contractor may be entitled (Clause 4.4.13)"[14]. In summary, the exceptions that may impact on-time performance are:

- Force Majeure
- Authority's actions
- Power failures out of contractor's control
- Accident or incidents caused by users (with exception of heavy boardings)

The last part of this clause determines when a late trip should be included in the estimation of the total late trips for a month and when it should be excluded. If the

[14] Ibid.

number of late trips is over the base (excluding the late trip caused by a permitted exception), the late trip is not included in estimating the penalty for that month. However, if the total of late trips is below the base (again excluding the excused late trip), the late trip is counted in determining the incentive to be awarded to the contractor. In section 3.2.1 an example will be presented to explain the impact of this clause in the estimation of late trips in on-time performance.

The contract terms and incentive and penalty structure were derived from the Metrobús' contract. Metrobús is a privately contracted bus service in the SJMA that runs in exclusive lanes. Basically, the contract terms were adjusted to reflect the nature of Tren Urbano; it appears that there was no exhaustive analysis undertaken to develop a unique set of incentives and penalties recognizing the difference between bus and rail transit service.

This research will analyze only the contract terms related to on-time performance and missed trips, because these are the standards that are vulnerable during a disruption on the line. Late trips caused during a non-routine disturbance are inevitable. If short turning, expressing or deadheading strategies are applied, trains will skip certain stations. If a train is short turned it does not complete its trip in the original travel direction. The structure of the Tren Urbano on-time performance contract terms is unique, and consequently requires careful analysis to ensure that the financial interests of the operator are perfectly aligned with the Authority objectives and the interest of passengers. A poor structure might lead to operator actions that might negatively impact service quality, even though the performance meets the standards established in the contract.

3.2 On-time Performance Contract Terms

Researchers agree that on-time performance is one of the most important measures of reliability, according to the riders' expectations. According to Strathman et al (1999), many studies have shown that unreliable service leads to lost patronage, revenue and public support because passengers will tend to choose another transportation alternative that better meets their expectations. Transit agencies commonly use on-time performance as one performance standard (along with other measures) for all types of services (rail, bus, and commuter rail).

The following subsections introduce both the on-time performance and missed trip clauses in the Tren Urbano O&M Contract. It includes the incentive and penalty structure designed by the Authority.

3.2.1 On-time Performance

With respect to on-time performance, Clause 4.4.1 (page 34) states: "...A train shall be deemed off-schedule if it completes its trip (arrives at the terminal station) more than one minute prior to the scheduled trip time, or more than the lesser of (a) three minutes and (b) one half of the headway on which the train is scheduled to operate, after the scheduled trip time... If a train skips one or more stations on any trip, each station skipped shall be counted as an off-schedule train... Trains counted as missed trips should not be counted as an off schedule train."[15]

Tables 3-2 and 3-3 present the scheme to be followed to determine the incentive or penalty payment for each month. Table 3-2 presents the base number of allowed off-schedule trips for each month based on 4 off-schedule trips allowed per day. The difference between months simply results from the number of days in each month. Table 3-3 shows the incentive/penalty structure, which depends on how many trips are off-schedule compared with the base number. For example, if during January the system had only 104 off-schedule trips, this means that they are 20 trips below the base number of 124; therefore, they receive an incentive payment of $11,000. Note that the number of permitted off-schedule trips is independent of time of day, and does not distinguish between weekdays and weekends. Table 3-3 represents the incentive/penalty scheme for the second (and later) year(s) of revenue service.

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[15] Ibid.

Figure 3-1 is a graphical representation of Table 3-3. The incentive/penalty structure for 74 to 174 late trips is described by a step function. There are some characteristics that stand out in this region of the incentive/penalty structure. First, the increase between steps is not constant. For example, for 125-134 late trips the penalty is $5,000, and for 135-144 late trips the penalty is $11,000, an increase of $6,000. Then, for 145-154 late trips the penalty rises to $18,000, which represents a $7,000 increase.

A second point that stands out with this incentive/penalty structure is that, for example, 125 late trips are valued the same as 134 late trips, even though there is an increase of 9 late trips. The marginal cost of an additional trip in this range is $0. However, when the number of late trips increases from 134 to 135, the marginal penalty for the additional late trip is $6,000. Then, from 135 to 144 late trip, the marginal penalty is again $0. This pattern is repeated with every step in the penalty function, meaning that the marginal penalty ranges from $0 to $9,000. Then, when there are over 175 late trips, the marginal penalty becomes constant at $750 per late-trip. The same behavior is observed in the incentive structure.

For the first year the penalty structure is different, varying every three months although the incentive structure is the same as in later years as shown in Tables 3-4 through 3-7. In the first year the penalties start out at a low level but become more severe every three months until the end of the first year of revenue service, when the penalty increases greatly to reach its long-term level as shown in Figure 3-2. The increase every three months during the first year is constant for a given number of off-schedule trips. For example, the penalty for 135-144 off-schedule trips/month for the first quarter is $250, which increases by $250 every three months until the last quarter of the first year, in which the penalty is $1,000. From the second year on, the penalty increases to $11,000. Note the significant increase ($10,000) from the last quarter of the first year to the second year.

Table 3-2 On-time Performance: Base Numbers of Off-Schedule Trips Permitted Per Month

Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
124	112	124	120	124	120	124	124	120	124	120	124

Source: Phase I of Tren Urbano: Systems and Test Track Turnkey Contract – Contract Book II

Table 3-3 On-Time Performance: Incentive/Penalty Structure

# of Off-schedule Trips per Month		Incentive/Penalty Structure for Subsequent Years to First Year of Revenue Service	
General	**Example (Base = 124)**	**Incentive**	**Penalty**
Less than (Base-50)	Less than 74	(Base - #trips) x $750.00	-
(Base-50) - (Base-41)	74-83	$35,000	-
(Base-40) - (Base-31)	84-93	$26,000	-
(Base-30) - (Base-21)	94-103	$18,000	-
(Base-20) - (Base-11)	104-113	$11,000	-
(Base-10) - (Base-1)	114-123	$5,000	-
Base number	124	No incentive	No penalty
(Base+1) - (Base+10)	125-134	-	$5,000
(Base+11) - (Base+20)	135-144	-	$11,000
(Base+21) - (Base+30)	145-154	-	$18,000
(Base+31) - (Base+40)	155-164	-	$26,000
(Base+41) - (Base+50)	165-174	-	$35,000
More than (Base+50)	More than 175	-	(#trips – Base) x $750.00

Source: Phase I of Tren Urbano: Systems and Test Track Turnkey Contract – Contract Book II

Figure 3-1 On Time Performance - Incentive/Penalty Structure as a Function of Off-Schedule Trips

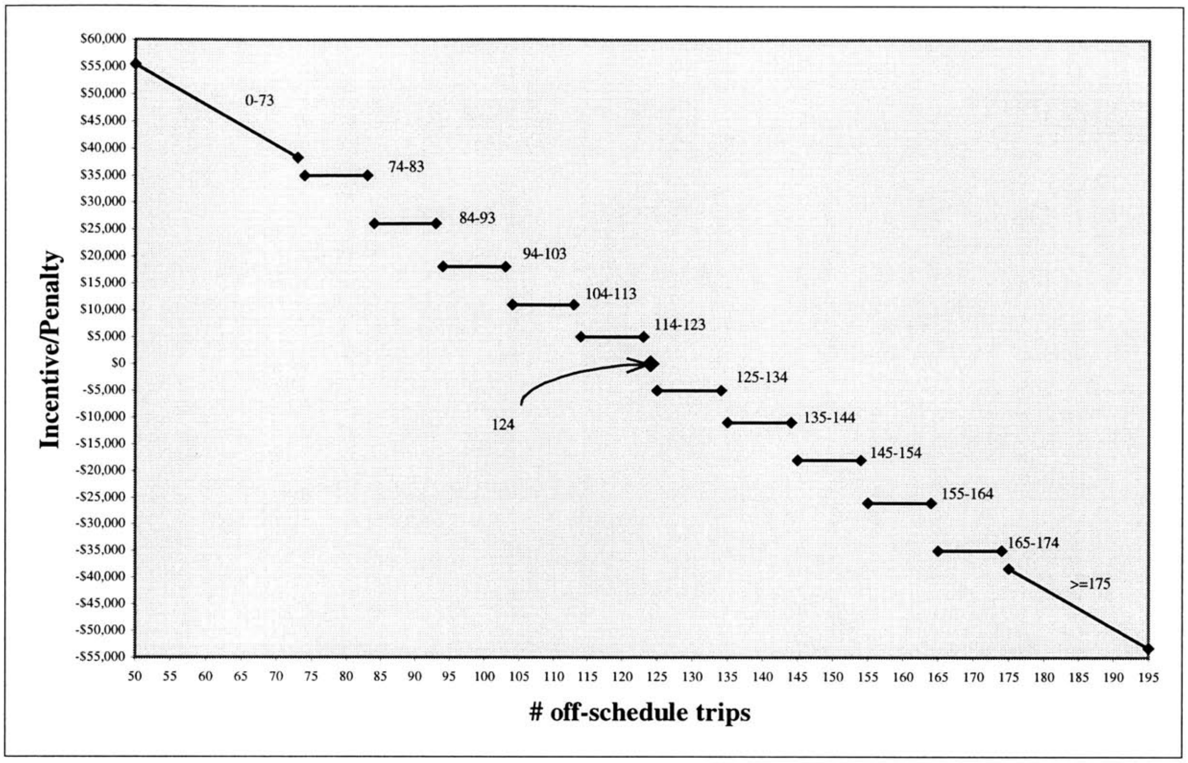


Table 3-4 On-Time Performance – Incentive/Penalty Structure: Months 1-3

# of Off-schedule Trips per Month		Incentive/Penalty Structure	
General	Example (Base = 124)	Incentive	Penalty
Less than (Base-50)	Less than 74	(Base - #trips) x $750.00	-
(Base-50) - (Base-41)	74-83	$35,000	-
(Base-40) - (Base-31)	84-93	$26,000	-
(Base-30) - (Base-21)	94-103	$18,000	-
(Base-20) - (Base-11)	104-113	$11,000	-
(Base-10) - (Base-1)	114-123	$5,000	-
Base number	124	No incentive	No penalty
(Base+1) - (Base+10)	125-134	-	0
(Base+11) - (Base+20)	135-144	-	$250
(Base+21) - (Base+30)	145-154	-	$750
(Base+31) - (Base+40)	155-164	-	$1,500
(Base+41) - (Base+50)	165-174	-	$2,500
More than (Base+50)	More than 175	-	(#trips – Base) x $50.00

Source: Phase I of Tren Urbano: Systems and Test Track Turnkey Contract – Contract Book II

Table 3-5 On-Time Performance – Incentive/Penalty Structure: Months 4-6

# of Off-schedule Trips per Month		Incentive/Penalty Structure	
General	Example (Base = 124)	Incentive	Penalty
Less than (Base-50)	Less than 74	(Base - #trips) x $750.00	-
(Base-50) - (Base-41)	74-83	$35,000	-
(Base-40) - (Base-31)	84-93	$26,000	-
(Base-30) - (Base-21)	94-103	$18,000	-
(Base-20) - (Base-11)	104-113	$11,000	-
(Base-10) - (Base-1)	114-123	$5,000	-
Base number	124	No incentive	No penalty
(Base+1) - (Base+10)	125-134	-	0
(Base+11) - (Base+20)	135-144	-	$500
(Base+21) - (Base+30)	145-154	-	$1,500
(Base+31) - (Base+40)	155-164	-	$3,000
(Base+41) - (Base+50)	165-174	-	$5,000
More than (Base+50)	More than 175	-	(#trips – Base) x $125.00

Source: Phase I of Tren Urbano: Systems and Test Track Turnkey Contract – Contract Book II

Table 3-6 On-Time Performance – Incentive/Penalty Structure: Month 7-9

# of Off-schedule Trips per Month		Incentive/Penalty Structure	
General	Example (Base = 124)	Incentive	Penalty
Less than (Base-50)	Less than 74	(Base - #trips) x $750.00	-
(Base-50) - (Base-41)	74-83	$35,000	-
(Base-40) - (Base-31)	84-93	$26,000	-
(Base-30) - (Base-21)	94-103	$18,000	-
(Base-20) - (Base-11)	104-113	$11,000	-
(Base-10) - (Base-1)	114-123	$5,000	-
Base number	124	No incentive	No penalty
(Base+1) - (Base+10)	125-134	-	0
(Base+11) - (Base+20)	135-144	-	$750
(Base+21) - (Base+30)	145-154	-	$2,250
(Base+31) - (Base+40)	155-164	-	$4,500
(Base+41) - (Base+50)	165-174	-	$7,500
More than (Base+50)	More than 175	-	(#trips – Base) x $175.00

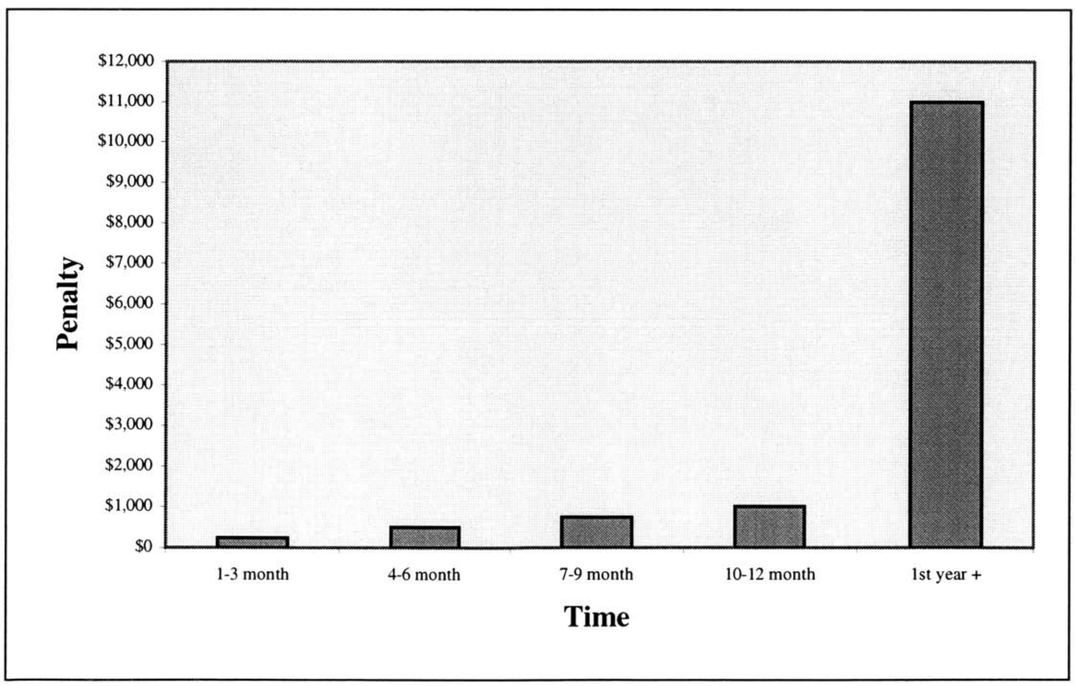
Source: Phase I of Tren Urbano: Systems and Test Track Turnkey Contract – Contract Book II

Table 3-7 On-Time Performance – Incentive/Penalty Structure: Months 10-12

# of Off-schedule Trips per Month		Incentive/Penalty Structure	
General	Example (Base = 124)	Incentive	Penalty
Less than (Base-50)	Less than 74	(Base - #trips) x $750.00	-
(Base-50) - (Base-41)	74-83	$35,000	-
(Base-40) - (Base-31)	84-93	$26,000	-
(Base-30) - (Base-21)	94-103	$18,000	-
(Base-20) - (Base-11)	104-113	$11,000	-
(Base-10) - (Base-1)	114-123	$5,000	-
Base number	124	No incentive	No penalty
(Base+1) - (Base+10)	125-134	-	0
(Base+11) - (Base+20)	135-144	-	$1,000
(Base+21) - (Base+30)	145-154	-	$3,000
(Base+31) - (Base+40)	155-164	-	$6,000
(Base+41) - (Base+50)	165-174	-	$10,000
More than (Base+50)	More than 175	-	(#trips – Base) x $250.00

Source: Phase I of Tren Urbano: Systems and Test Track Turnkey Contract – Contract Book II

Figure 3-2 Penalty Structure Transition through First Year of Revenue Operation



When there is a delayed trip caused by any of the exceptions mentioned in section 3.1, this trip would be excluded in determining the number of off-schedule trips if by the end of the month the number of late trips is over the base number (exceptions included). However, in the case that the number of late trips is below the base number, off-schedule trips would be included to determine the incentive awarded to the contractor during that month. For example, assume that in January the contractor had 134 late trips, without including a late trip that was caused by a medical emergency in a train. Even though the total late trips were 135, the contractor would be penalized for 134 late trips. On the other hand, assuming that there were 83 late trips (without including the late trip caused by a medical emergency), the incentive to the contractor will be estimated based on 84 late trips. Indirectly, the contractor is being penalized for that late trip when being rewarded for meeting the on time performance standard.

The base number represents, as mentioned before, an average of 4 late-trips per day. The weekday trip schedule specified in the Operation & Maintenance plan includes a total of 326 daily trips; during the weekends there are 202 trips per day. Assuming a 28-day month, the total number of trips is (326 x 20) + (202 x 8) = 8136 trips/month. Since the number of off-schedule trips per month should be less than 1.5% of the total trips, then 8136 x 0.015 = 122 late-trips/month. This represents an average of 4 late-trips per day, which is used to estimate the number of off schedule allowed in 30 and 31 days months.

3.2.2 Missed Trips

With respect to missed trips, Clause 4.4.2 (page 35) states: "... A scheduled trip is not completed if (i) it is cancelled or dropped from schedule, or (ii) the train running the trip is removed from service before completing the trip (arriving at the terminal station), or (iii) the train running the trip arrives at the terminal more than a half hour after scheduled trip time. A train not containing the schedule consist (but completing its trip) shall be counted as one-half of a missed trip."[16]

[16] Ibid.

Table 3-8 presents the incentive/penalty structure for missed trips with Figure 3-3 providing a graphical representation. In this case the base number is 30 missed trips/month (approximately 1 per day), with monthly penalties or incentives being assessed for deviations as shown in Table 3-8. The incentives and penalties are structured in such a way that the penalty for a missed trip over the base number is approximately an order of magnitude greater than the incentive for missing one less trip below the base number. For example, each trip missed over a level of 36 trips in a month will result in an additional penalty of $10,000. However, if we have the opposite situation, each missed trip below 24 will result in an increase in the incentive of $1,200. Table 3-8 presents the incentive/penalty structure starting in month 10 of operation. The first three quarters of revenue operation during the first year have a different penalty structure that changes every three months although the incentives are the same from the start of revenue operation. However, the penalty structure increases over the first year, until it reaches a constant value by the last quarter of the first year of revenue service as show in Tables 3-9 through 3-11. For example, for 31 missed trips the penalty is $1,250 and this amount increases every three months, until the last quarter, when the penalty reaches a constant value of $5,000. Unlike the off-schedule penalty structure, the difference between the first year of operation and subsequent years is not drastic, as shown in Figure 3-4.

3.3 Analysis of Contract Terms

The contract terms were carefully analyzed to determine areas that might result in conflicts with respect to providing high service quality and that might lead to undesirable actions by the controller. This analysis presents contract elements that may not result in the desired transit operations management practices.

Table 3-8 Missed Trips – Incentive/Penalty Structure

Number of missed trips per month	Incentive	Penalty
Less than 24	$5,400 + $1,200 x (24 - #missed trips)	-
24	$5,400	-
25	$4,200	-
26	$3,100	-
27	$2,100	-
28	$1,200	-
29	$500	-
30 (base number)	No incentives	No penalties
31	-	$5,000
32	-	$11,000
33	-	$18,000
34	-	$26,000
35	-	$35,000
36	-	$45,000
More than 36	-	$45,000 + $10000 x (#missed trip - 36)

Source: Phase I of Tren Urbano: Systems and Test Track Turnkey Contract – Contract Book II

Figure 3-3 Missed Trips - Incentive/Penalty Structure First Year (Months 10-12) and Subsequent Years

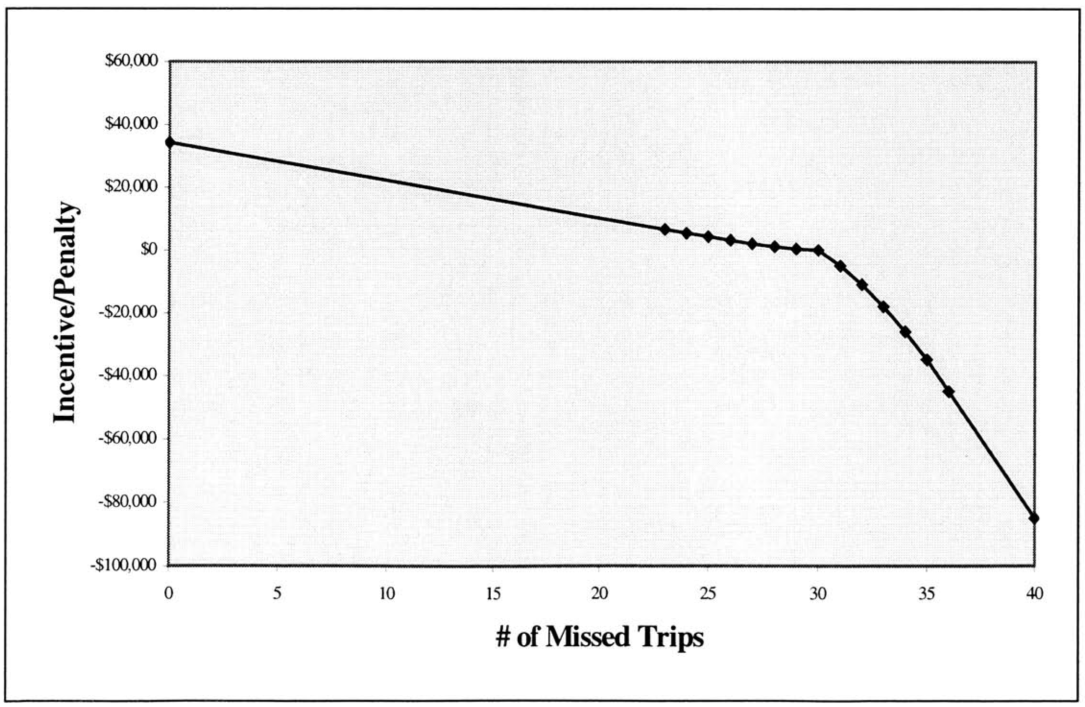


Table 3-9 Missed Trips – Incentive/Penalty Structure: First 3 Months

Number of missed trips per month	Incentive	Penalty
Less than 24	$5,400 + $1,200 x (24 - #missed trips)	-
24	$5,400	-
25	$4,200	-
26	$3,100	-
27	$2,100	-
28	$1,200	-
29	$500	-
30 (base number)	No incentives	No penalties
31	-	$1,250
32	-	$2,750
33	-	$4,500
34	-	$6,500
35	-	$8,750
36	-	$11,250
More than 36	-	$11,250 + $2,500 x (#missed trip - 36)

Source: Phase I of Tren Urbano: Systems and Test Track Turnkey Contract – Contract Book II

Table 3-10 Missed Trips – Incentive/Penalty Structure: Months 4-6

Number of missed trips per month	Incentive	Penalty
Less than 24	$5,400 + $1,200 x (24 - #missed trips)	-
24	$5,400	-
25	$4,200	-
26	$3,100	-
27	$2,100	-
28	$1,200	-
29	$500	-
30 (base number)	No incentives	No penalties
31	-	$2,500
32	-	$5,500
33	-	$9,000
34	-	$13,000
35	-	$17,500
36	-	$22,500
More than 36	-	$22,500 + $5,000 x (#missed trip - 36)

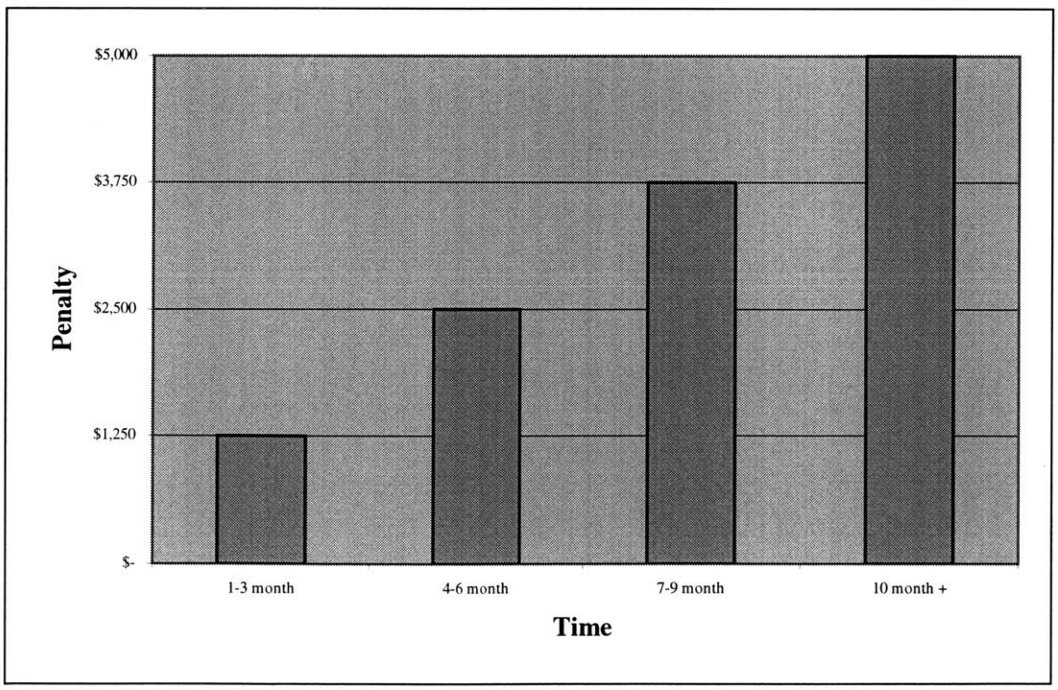
Source: Phase I of Tren Urbano: Systems and Test Track Turnkey Contract – Contract Book II

Table 3-11 Missed Trips – Incentive/Penalty Structure: Months 7-9

Number of missed trips per month	Incentive	Penalty
Less than 24	$5,400 + $1,200 x (24 - #missed trips)	-
24	$5,400	-
25	$4,200	-
26	$3,100	-
27	$2,100	-
28	$1,200	-
29	$500	-
30 (base number)	No incentives	No penalties
31	-	$3,750
32	-	$8,250
33	-	$13,500
34	-	$19,500
35	-	$26,250
36	-	$33,750
More than 36	-	$33,750 + $7,500 x (#missed trip - 36)

Source: Phase I of Tren Urbano: Systems and Test Track Turnkey Contract – Contract Book II

Figure 3-4 Missed Trips - Penalty Structure Transition (# of missed trips = 31)



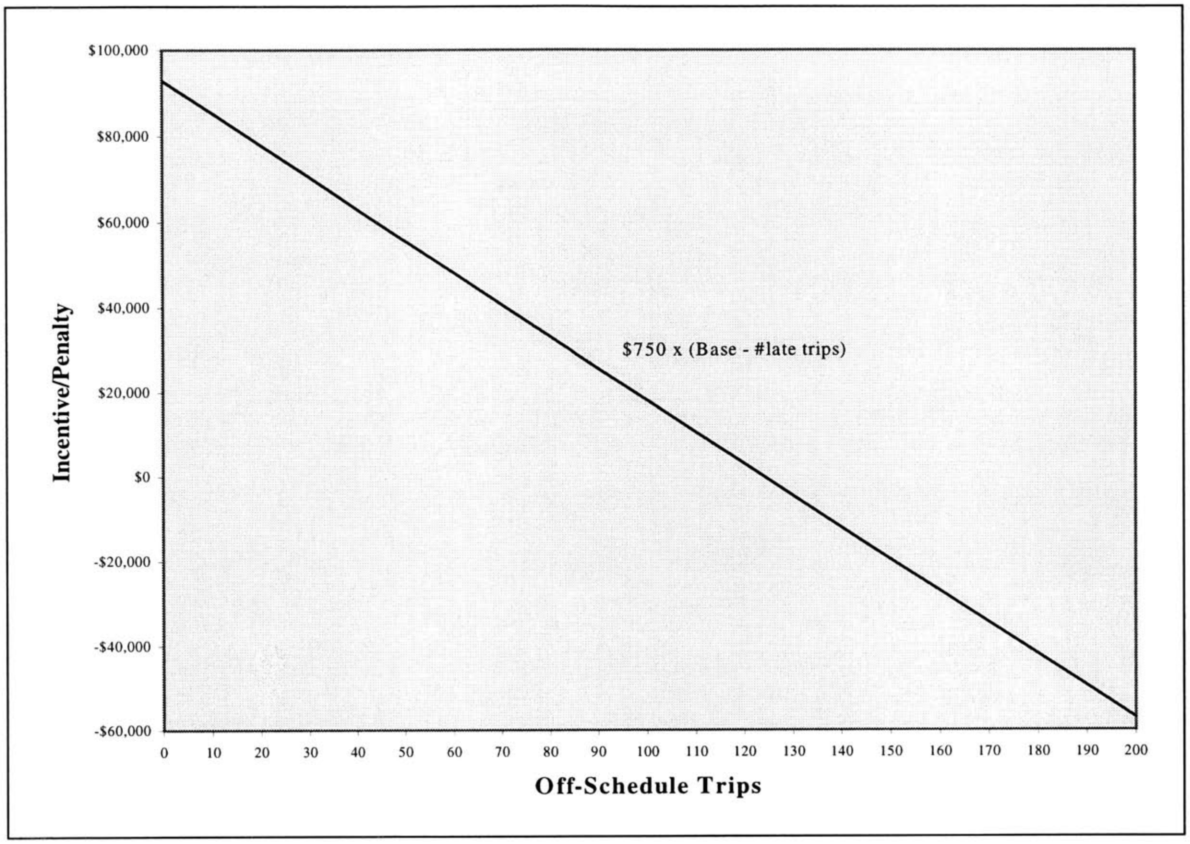
1. The first problem encountered in the incentive/penalty structure for on-time performance is the step function behavior shown in Figure 3-1. As mentioned before, there is no distinction in financial impact between, 125 trips and 134 trips, even though there is a difference of 9 missed trips. The step function covers a range of off-schedule trips that are affected either by incentives or penalties. In the case of incentives, the contractor is not rewarded differently if he had only 74 off-schedule trips in one month and 83 off-schedule trips the next month. The incentive received would be the same in both cases. Similarly, if one month the contractor has 125 off-schedule trips, and 134 off-schedule trips the next month, he will be penalized the same amount in both months. In many cases this gives the contractor no incentive to avoid one off-schedule trip since he will be equally rewarded/penalized in either case. It may be argued that the incentive/penalty structure was designed to reflect the fact that in a disruption situation, there will be more than one off-schedule trip. For example, as a result of a 10-minutes disruption, at least 5 trains will arrive late at the terminal, independent of the control strategies applied. However, the incentives and penalties should be structured to motivate the provision of the best service quality possible. By providing a range of performance with the same financial impact, the contractor has the option of performing at the extreme that requires the least effort.

   For less than 74 late trips and more than 175 late trips the equation that describes the incentive/penalty structure is:

$$Incentive\,/\,Penalty = \$750 * (Base\ Number - \#\,late\ trip) \qquad (3\text{-}1)$$

   where a positive value is an incentive, and a negative value is a penalty. A potential alternative incentive/penalty structure is to use this definition independent of the number of late trips, as shown in Figure 3-5. Another alternative is to separate the structure of incentive from the penalties, similar to the missed trips clause (see Figure 3-3). A steeper slope than the incentive slope can be used to describe the penalty structure, which represents more severe treatment if the standards are not meet. Later in Chapter 6, we will summarize the potential options for the incentive/penalty restructuring and make recommendations.

Figure 3-5 On Time Performance - Alternative Incentive/Penalty Structure



2. On time performance is defined by identifying off-schedule trains based on deviations from the schedule. However, when headways are less than 10 minutes, the most important consideration for passengers will be headway consistency rather than schedule adherence. Schedule adherence is very important when the frequency is low and passengers tend to rely on the schedule. The distinction between high and low frequency services was first addressed by Welding (1957). As mentioned in Chapter 2, passenger arrivals in high frequency systems are random. Equation 2-1 shows that passenger waiting time in that case depends heavily on the variance of headway. In the case of TU, the scheduled headways range between 4 and 12 minutes; therefore, it would be better to define on time performance in terms of headway adherence rather than schedule adherence. As will be discussed in Chapter 5, the Automatic Train Regulation (ATR) system of TU has the capability to modify the train velocity and

dwell time in order to adjust headway, which allows the use of headways as a measure of on-time performance rather than relying strictly on schedule adherence. For example, during a routine disturbance, if a particular train headway increases due to heavy boardings at a station, the speed of the vehicle can be adjusted to maintain the scheduled headway. If a longer disruption occurs, the ATR will first minimize the headway variance, and then adjust performance to achieve the scheduled headway, which represents an effective way of dealing with disturbances.

3. The first part of the on-time performance clause says that a train shall be deemed off-schedule if it arrives more than one minute early at the terminal. It may be argued that at the terminal station in particular it is not a problem if the train arrives earlier than the scheduled time. The impacts of arriving earlier than the scheduled time at the terminal station are (1) passengers on-board arrive earlier at their destination (which is positive), and (2) the recovery time of that train will be longer than scheduled. If we are interested in measuring the schedule adherence of the system it should be measured at each individual station where boarding occurs, given that failure to maintain schedule adherence affects passenger waiting time. The on-time performance should be measured at various points along the line, for example, near the beginning of the line, at the center, and near the end of the line, or at points where boardings are high. Choosing points en route is preferable to using the terminal because the former serve more customers (Nakanishi, 1997); therefore, on-time performance at those points is expected to cause more impact on customers. During the morning peak hour, the typical boarding/alighting pattern is to have heavy boardings before the CBD, and heavy alightings in the CBD. This means that service may start to degrade at the point where boardings are heavy and continue along the rest of the line. Choosing points before the CBD will allow the transit agency to assess whether actions are needed to improve service if they reflect poor performance. Another important suggestion is to consider different points at which to measure on-time performance depending on the direction of travel and time of day. AM Peak and PM Peak present different boarding/alighting pattern, as well as different dominant directions of travel. For example, for a route that crosses the

CBD, the heavy boarding stations in both directions might be located in different locations before the CBD.

In the case of Tren Urbano, the AM peak-hour heavy boarding locations in the San Juan direction are Bayamón Centro, Complejo Deportivo, Cupey and Río Piedras, as shown in Table 3-12. Table 3-13 shows that heavy alightings occur at Universidad, Roosevelt, Hato Rey and Sagrado Corazón. The CBD could be defined near the end of the alignment in the direction toward San Juan, at the stations serving the areas of Río Piedras and Hato Rey. In the Bayamón direction, the heavy boardings are expected to be at Sagrado Corazón, and from Río Piedras. The stations with heavy alightings are Universidad, Deportivo and Bayamón. Given these characteristics, at the beginning of revenue service on-time performance in the AM peak could be measured at some (or all) of these stations. The best locations to measure performance might change, depending on the system ridership patterns after opening. The suggestion presented above is based on the expected ridership data from demand models, and might not accurately reflect the real ridership when revenue service begins. The recommendation can be further extended to measure performance at all stations, because real time information on train location is available for all trips.

4. Given that arriving early only at the terminal station can result in penalties to the contractor, he may be motivated to hold trains when it is not appropriate. Holding trains unnecessarily implies increases in passenger travel time, which negatively affects service quality.
5. The second part of the on time performance clause says that when a train skips a station it is considered an off-schedule train. Usually, a train skips a station as part of real time control strategies such as deadheading, expressing or short turning. Penalizing a trip which is being controlled to get back to 'normal' operation may be counter-productive. In addition, it says that 'each skipped station is an off-schedule train', which is a severe penalty, given that a single train trip could be counted as several off-schedule train trips. For example, if a train skips Jardines and Cupey stations on the same trip, the contract terms would define this as two off-schedule trips. It appears that the penalty is structured this way to treat each skipped station as

a missed trip for that station; hence the heavy penalty, but the size of the penalty may well discourage the contractor from implementing the best recovery strategy for a disruption.

Table 3-12 Boardings and Arrival Rates – AM Peak Hour

Station Name	To San Juan		Station Name	To Bayamón	
	Arrival Rate (pass/min)	Normal Boardings (per train)		Arrival Rate (pass/min)	Normal Boardings (per train)
Bayamón	57.2	229	Sagrado Corazón	18.1	72
Deportivo	23.4	94	Hato Rey	4.3	17
Jardines	5.1	20	Roosevelt	4.5	18
Torrimar	4.5	18	Domenech	2.6	10
Martínez Nadal	3.8	15	Piñero	2.1	8
Las Lomas	7.0	28	Universidad	9.8	39
San Francisco	6.6	26	Río Piedras	16.2	65
Centro Médico	7.8	31	Cupey	6.9	28
Cupey	17.2	69	Centro Médico	2.3	9
Río Piedras	17.1	68	San Francisco	1.1	4
Universidad	5.2	21	Las Lomas	1.5	6
Piñero	6.8	27	Martínez Nadal	1.7	7
Domenech	1.2	5	Torrimar	0.8	3
Roosevelt	0.6	2	Jardines	1.4	6
Hato Rey	0.5	2	Deportivo	0.1	0
Sagrado Corazón	0.0	0	Bayamón	0	0

Table 3-13 Alightings and Alighting Fractions – AM Peak Hour

Station Name	To San Juan		Station Name	To Bayamón	
	Alighting Fraction	Normal Alightings (per train)		Alighting Fraction	Normal Alightings (per train)
Bayamón	0.0000	0	Sagrado Corazón	0.0000	0
Deportivo	0.0003	0	Hato Rey	0.0000	0
Jardines	0.0120	4	Roosevelt	0.0149	1
Torrimar	0.0096	3	Domenech	0.0321	3
Martínez Nadal	0.0317	11	Piñero	0.0437	5
Las Lomas	0.0220	8	Universidad	0.2467	29
San Francisco	0.0173	7	Río Piedras	0.1188	15
Centro Médico	0.0728	29	Cupey	0.1491	26
Cupey	0.1147	46	Centro Médico	0.1228	22
Río Piedras	0.1172	50	San Francisco	0.1367	23
Universidad	0.2776	123	Las Lomas	0.0780	11
Piñero	0.0730	25	Martínez Nadal	0.0349	5
Domenech	0.0684	23	Torrimar	0.0772	11
Roosevelt	0.2614	85	Jardines	0.0591	8
Hato Rey	0.3466	84	Deportivo	0.4170	55
Sagrado Corazón	1.0000	160	Bayamón	1.0000	78

6. The operation and schedules of TU are based on simulations and models that estimate running times based on expected ridership, dwell times and other operational characteristics of the system; however, after opening the system, the contractor will know better how the system operates under real conditions. The contract gives a different incentive/penalty structure for the first year of service, which changes every trimester of that year. It seams reasonable to have variable penalties through the first year of operation to allow adjustments in the operation during the first year, and performance is not heavily penalized during this adjustment period. However, the current transition should be modified to be similar to the incentive/penalty transition for missed trips.

   For example, the dwell time for TU is estimated at 30 seconds at all stations. This dwell time might be too high under normal operations for some stations that have low passenger arrival rates particularly in the initial stage of revenue operation. If the dwell time at each station can be reduced by four seconds, the running time is reduced by one minute, and consequently the train would arrive one minute early at the terminal station. Given that trains are off-schedule if arriving more than one minute early, the operator would be likely either to hold trains unnecessarily before arriving at the terminal or maintain the 30 seconds dwell time, even if there are no more passengers boarding/alighting in a particular station. Adjusting dwell time to actual performance might decrease the actual running times, which could be compensated for by increasing the recovery time at the terminals. The adjustments to dwell times and changes in schedule are possible given the capabilities of the control system.

   In addition, if the operator maintains the design dwell time, even if it might be longer than necessary at some stations and times of day, we will have air conditioning and energy losses resulting from keeping the doors open longer. Reducing the dwell time represents savings in energy consumption, which translate into operating cost savings, as well as longer than necessary travel times, and perception of needless delay for passenger.

7. Given the capabilities of the ATR system to adjust performance in the case of routine disturbances, non-routine disruptions are expected to be the main cause of having late trains. Non-routine disruptions could result from power failures, medical

emergencies, track and signaling malfunctioning, vehicle breakdown, people on-tracks, among others. The exceptions to enforce the performance standards include situations caused by patrons (with exception of heavy boardings), power failures out of contractor's control, Force Majeure (hurricane, earthquake, an 'act of God'), or any Authority action. It is reasonable to include exceptions under circumstances that are clearly not the responsibility of the contractor, and recognize that any other non-routine disturbance could be classified as the contractor's responsibility. Track and signaling system failures, door malfunctioning, and vehicle breakdowns clearly depend on the design and on the level of maintenance for the rail system components. The contractor should clearly be encouraged to maintain high level of maintenance in the system, not only because it is part of the performance standards, but also to reduce the frequency of incidents that would be classified as the contractor's responsibility. However, the existing exceptions may be too generous, and it might be better to specify, for example, what situations involving the users are exceptions. A medical emergency could be an appropriate exception because the contractor has no control over this kind of situation, however, the contractor should be responsible for resolving the situation in a short period, which minimizes its effects on the performance of the system. Another example is an incident caused by an user that could have been avoided if there were better security and vigilance, which are responsibilities of the contractor.

To simplify the enforcement of the contract provisions, the current exceptions should be reduced. The contractor may easily reach the 98.5% standard for on-time performance, because any disruptions may easily fit into one of the current exception, except for system and vehicle maintenance related disruptions. For example, the exceptions could be reduced to Force Majeure and Authority's actions. In addition, with the current on-time performance definition, any disruption will result in more than one late trip, and those additional late trips are included in the total number of late trips. The 1.5% allowance for late trips may be increased to account for late trips that are caused by Patrons (i.e. medical emergencies), power failures and the additional late trips indirectly caused by these disruptions. An advantage of such reduction in the exceptions is to reduce the scope for disagreement between the contractor and the Authority on the cause of a late train.

Another weakness that can be found in the exception structure is how the incentive is calculated considering a late trip that is classified as an exception. If the contractor had total late trips during a month below the base (including the excused late trips), the incentive is estimated considering that total of late trips. For example (and using the current incentive structure), let us assume there were a total of 114 late trips, but 3 late trips were caused by a power failure that was not the responsibility of the contractor. Instead of being rewarded for 111 late trips (which is an incentive of $11,000), the contractor will be rewarded for 114 late trips ($5,000). Indirectly, the contractor is being penalized for late trains that were caused by circumstances beyond his control.

8. As discussed in section 3.2.1, the base number for late trips represents 1.5% of the total trips in a month. In the case of missed trips, the performance standard allows about one missed trip per day, or 30 per month (the base number for incentive/penalty calculation). This represents approximately 0.3% of the total trips in a month, meaning that 99.7% of the trips should be completed. The percent of trains meeting the on time performance standard is set to 98.5%, which is a reasonable value for a rapid rail system that operates in its own right-of way. Similarly, a standard of 99.7% of completed trips during a month seems reasonable for a rail transit system.

3.4 On-time Performance Measures

This research includes two approaches to change the current structure of the on-time performance contract terms. The first approach to restructure the contract terms, which is presented in this section, consists of a review of performance measures used in rapid rail transit systems. The second approach is to analyze the impact of the contract terms on service quality during disruptions, given two control strategy alternatives: optimal solution and hypothetical Tren Urbano solution. The latter approach will be presented in Chapter 4.

In 1995, MacDorman & Associates and Wilson produced a report for the MBTA that reviewed the service quality measures and standards from 10 of the largest North American transit systems, including six light rail and rapid transit systems. The six systems are Chicago Transit Authority (CTA), Philadelphia's Southeastern Pennsylvania Transportation Authority (SEPTA), Portland's Tri-County Metropolitan Transit District of Oregon (Tri-Met), San Francisco Municipal Railway (MUNI), Toronto Transit Commission (TCC), and Washington Metropolitan Area Transit Authority (WMATA). The study was used to develop the Service Delivery Policy of the MBTA (September 1996).

The measure most used in transit agencies to estimate service reliability is schedule adherence, which is defined as the percent of trips that are on time. Table 3-14 summarizes the practices of the transit systems (light and rapid transit) studied including the MBTA. Aside from SEPTA, rapid transit systems base their measure of service quality based on performance relative to headway. In the case of the MBTA, headways are measured at one point away from the CBD and at point in the CBD for each rail transit line. As mentioned in the report, "this approach recognizes that passengers on frequent services (i.e., less than 10 minute headway) generally are more interested in regular, even headways than in strict on-time performance because they do not consult timetables when they use the services"[17]. Even though transit agencies measure service quality, there is no standard to evaluate their actual performance for all rapid transit systems presented here (with the exception of SEPTA).

Missed trip measures were not reported by the rapid transit agencies included in the study. This measure was mainly used in other transit systems such as buses and light rail. According to the report, the reasons not to use missed trips on rapid transit as a measure of service reliability are their low incidence and the fact that when failures occur they usually result in reductions in the train consist and not the elimination of trips. The

[17] MacDorman & Associates, Wilson, Nigel H.M. *Design of Service Quality Measures and Service Evaluation Standards: Final Report.* November 27, 1995.

four measures found among the surveyed systems were: (1) percent missed trips, (2) average missed trips per day, (3) percent completed trips, and (4) percent of service hours missed. For light rail systems, the measure used was percent of trips completed ranging from 99.8% to 99.9%; the exception was San Francisco MUNI that measures the percentage of service hours missed (1% standard). The MBTA records and reports the number of missed trips for all its transit services, including rapid transit; however, the report does not mention if there is any performance standard related to this measure for rail transit, only for light rail. The missed trips standard for the MBTA light rail system is 99.9% trips completed.

Table 3-14 On-time Performance Standard for USA & Canada Transit Systems

System	Measure	Standard
Philadelphia SEPTA (light rail & rapid transit)	% trips 0-5 min late from scheduled arrival	Headway ≤ 10 min: *Peak – 75%* *Off-Peak & Weekends – 80%* Headway > 10 min: *Peak – 85%* *Off-Peak & Weekends – 95%*
Toronto TCC (rapid transit)	% trip wait time more than 60 sec greater than scheduled headway	No standard
Washington, DC WMATA (rapid transit)	% trip wait time more than 2 minutes greater than scheduled headway	No standard
Boston MBTA (rapid transit)	*1977 Service Policy* % of passengers waiting more than 2 scheduled headways *1996 Service Delivery Policy* % of all trips completed within 1.5 headway % of all trips within 5 minutes of scheduled trip time	*1977 Service Policy* No standard *1996 Service Delivery Policy* 95% 95%

Source: *Design of Service Quality Measures and Service Evaluation Standards: Final Report*

The report recommends that rapid transit systems use as schedule adherence measures the percent of trips within 1.5 times the scheduled headway ($1.5H_{scheduled}$) and the percent of trips with travel time no more than 5 minutes greater than scheduled travel time ($TT_{scheduled}+5$), as shown in Table 3-14. The first measure recognizes that frequent customers expect regular, even headways rather than following a schedule because they do not use a timetable when using such frequent services. The latter is to conform to passengers' expectation of having travel times that have low variation with respect to the scheduled travel time. For both measures a standard of 95% is recommended. It is reasonable for rapid transit services since they operate in their own right-of-way and their operation is not subject to interference in the same way as other types of transit service. In addition, the data collection required from the MBTA to support these standards showed that they are reasonable.

A study performed by the University of Portland and Tri-Met, the transit provider of the Portland, Oregon metropolitan region, proposed the use of four measures of service reliability in addition to the typical on-time performance (Strathman et al, 1999). These additional reliability measures are: Headway Ratio (HR), Run Time Ratio (RTR), Coefficient of Variation of HR and RTR (CV_{HR} and CV_{RTR}), and Excess Wait (EW). The equations describing these measures are as follows:

$$HR = \frac{H_{Observed}}{H_{Scheduled}} * 100 \qquad (3\text{-}2)$$

$$RTR = \frac{Run\ Time_{Observed}}{Run\ Time_{Scheduled}} * 100 \qquad (3\text{-}3)$$

$$CV_{HR} = \frac{Standard\ Deviation_{HR}}{Mean_{HR}}, \quad CV_{RTR} = \frac{Standard\ Deviation_{RTR}}{Mean_{RTR}} \qquad (3\text{-}4)$$

$$EW = \frac{[Variance\ HR / 2HR_{Mean}]}{100} * H_{average} \qquad (3\text{-}5)$$

HR is useful for frequent service for the same reasons stated previously for the use of headway adherence. RTR is also a good measure of reliability particularly for bus or light rail systems that are subject to external influences, other than heavy loading or incidents, that might affect the regularity of running times. The CV allows comparing the variation of these measures across routes and times. The EW estimates the passenger's average excess waiting time at the point headway variation is measured. Having such a variety of measures for reliability help to provide a broader view of the quality of service provided to riders, in addition to providing a basis for developing service improvements.

3.5 Initial Restructuring to Contract Terms given Current Practice in Transit Systems

The following initial proposals for restructuring the contract terms related to on-time performance are based on the discussions above and are simply presented as a starting point for further discussion. The final proposed restructuring will be based on the results of the impact on service quality in the event of a disruption in the system from Chapter 4.

On time performance:

1. Redesign the incentive/penalty structure by penalizing each individual late trip. The structure can be similar to the missed trips structure, where penalties are more severe than incentives, or use a linear relation in which each late trip is given a fixed penalty.
2. Base on-time performance on headways. For example, an off schedule trip could be defined as one with a departing headway at any station greater than 2 minutes over the scheduled headway ($H_{scheduled}$+2 minutes). The base level of performance in terms of this definition of on-time performance could be 98.5%, permitting 4 trips per day to be off-schedule without incurring penalties or receiving incentives. If the exceptions are reduced to simplify monitoring and assessment of late trips, as recommended below, the allowance of 1.5% of late trips could be

increased to account for situations that previously were considered exceptions, but that were not included in the revised definition.

Late trip exceptions should not be accounted for to estimate the compensation for the contractor. This can be perceived as penalizing the contractor, even though the circumstances under which the trip was delayed are not the responsibility of the contractor. In addition, the exceptions should be reduced to Force Majeure and Authority actions, because the current definition is too generous and might lead to a perception of good service quality, when in reality the service quality is poor. The broader the exceptions are, the greater number of late trips can be classified as an exception.

Another measure that might not be set as an incentive/penalty standard, but as a performance standard, is to measure the percent of passengers with a waiting time less than H+1 min or H+2 min (such as in Toronto and Washington, DC systems), where H is the scheduled headway. The contractor suggested in the proposal for the Management Information and Decision Support System (MIDSS) measuring the percent of passengers that wait more than $H_{schedule}$. The standard was defined as 99.5% of passengers waiting less than $H_{schedule}$.

A measure for on time performance recommended to the MBTA (and that is included in the *Service Delivery Policy*) is to measure the percent of trains that operate within 5 minutes (or whatever value is established as a threshold) of scheduled trip time. The MBTA goal is to have 95% of trains arriving within 5 minutes of scheduled trip time. A similar but a much higher standard could be considered as part of the contract structure for Tren Urbano operations, such as 98.5% of trips arriving within 2 minutes of scheduled trip time. The threshold for travel time can be lower in the case of Tren Urbano, given the ATR system capabilities of the system.

3. Define headway adherence at points other than the terminal. For Tren Urbano, headway adherence can be measured at all stations, because the monitoring system collects that data, and it would not represent any additional cost. Headway standards should be met at all stations, with the exception of a trip

arriving at a terminal, where there are no passengers boarding because that is the end of the trip.

4. Reconsider counting each skipped station as a late trip. First, if a train skips *n* stations in the same trip, it is equivalent to *n* late trips, which is a severe penalty that might discourage the contractor from using station-skipping strategies that might result in improved service quality during a disruption. It may be reasonable to penalize station skipping under circumstances that can be solved without taking such an action, but without the severity that is imposed in the current contract.

Chapter 4:

Disruption Analysis

As a result of a disruption, the trains that are directly affected will arrive late at the terminal. The controller's actions to minimize the impact of such a disruption will naturally be aimed at minimizing the financial impact of the disruption rather than strictly minimizing the impact on the passengers' perceived service quality. As discussed in Chapter 3, the contract terms should be structured in such a way that the financial interests of the contractor are perfectly aligned with the passengers' interests.

In this chapter, the control strategy options for Tren Urbano will be explored in order to develop a set of hypothetical control strategies based on the contract terms incentives and penalties (see Chapter 3). Using the model introduced in Chapter 2 in combination with a set of equations to estimate total passenger waiting time, both the Tren Urbano hypothetical control strategies and the optimal solution will be estimated and compared. The results will be analyzed to determine whether the existing contract terms are likely to compromise service quality, and if so, to what extent.

4.1 Tren Urbano Control Strategies Description

The contract terms structure is expected to influence the control strategy decisions during and after disruptions. This section describes the actions taken by the controller (in addition to the automatic control adjustments) to get the system back to normal operation after a disruption. The Automatic Train Regulation (ATR) system capabilities are not included in this analysis; they will be discussed in Chapter 5 of this thesis.

4.1.1 Holding

Holding is likely to be severely limited by the existing on-time performance clause that states that a train is classified as late if it arrives at the terminal "more than the lesser of (a) three minutes and (b) one half of the headway on which the train is scheduled to operate"[18]. This means that during peak periods, a train is allowed to arrive at the terminal 2 minutes late and during the off-peak period 3 minutes later than the schedule, and still be considered as on time. In the event of a disruption we would expect to hold one or more trains ahead of the blockage (see Chapter 2). If we hold one train ahead of the blockage, it can be held up to 2 minutes if running in the peak period and 3 minutes in the off-peak period before late on-time performance penalties are incurred for this train. If two trains are held in the peak period the first train could be held 1 minute and the following train held 2 minutes (in the interest of simplicity we will focus on integer minute holding times only). In the off-peak, the first train could be held up to 2 minutes and the following train up to 3 minutes. The model used to determine the optimal set of control strategies was modified with an additional constraint to obtain the optimal set of control of strategies, subject to the contract terms. The additional constraints that represent the contract terms are:

$$\sum_{all\ k \leq t} ht_{ik} \leq 2, \quad \forall \quad i\ ahead\ blockage, i \in T,\ for\ peak\ periods \qquad (4\text{-}1)$$

$$\sum_{all\ k \leq t} ht_{ik} \leq 3, \quad \forall \quad i\ ahead\ blockage, i \in T,\ for\ off-peak\ periods \qquad (4\text{-}2)$$

[18] Puerto Rico Highway and Transportation Authority, *Phase I of Tren Urbano: Systems and Test Track Turnkey Contract – Contract Book II Operations and Maintenance.* August 1995.

Equations 4-1 and 4-2 restrict trains ahead of the blockage to have a total holding time no greater than 2 or 3 minutes, depending on the time period. The summation of holding times is measured from the first station the trains could be held at to the terminal station.

4.1.2 Expressing and Deadheading

Because of the existing contract terms neither expressing nor deadheading are likely to be used by the controller, and hence will not be analyzed as part of this research. First, each skipped station is considered as a late trip. When a train is expressed or deadheaded it is because there is a long preceding headway and a short following headway. In the case of a disruption, this description corresponds to the disrupted train immediately after the blockage is cleared. Hence, this train is already late, and depending on the length of the disruption, it is very likely to be late when it arrives at the terminal. Second, expressing and deadheading contributions to minimizing impacts of a disruption are modest (Shen, 2000) and therefore can be excluded from the strategies studied here without greatly affecting service quality. However, the impacts of having a restriction on skipping stations will be analyzed as part of the short turning strategies below.

4.1.3 Short Turning

Short turning should be considered in lengthy disruptions. Short turning might be restricted by either the on-time performance or the missed trip contract clauses. When a train is short-turned, it skips a certain number of stations, which means that it would be counted as n late trains if the short-turned train skipped n stations. However, it could also be counted as a missed trip, since it never arrives at the terminal station. The contract does not specify how specific control strategies will be classified under this contract. We develop an analysis to determine the financial impact of considering short turning either as a late trip or as a missed trip and will draw conclusions from both scenarios. In the Tren Urbano context, if a train is short-turned between Cupey and Río Piedras stations (in either direction) it skips 17 stations. Given the worst case scenario, where the contractor already exceeded 175 late trips, the penalty incurred for short-turning a train would be

$750 x 17 trips = $12,750, in addition to the penalties already incurred for other late trips. In the case that it is classified as a missed trip, the maximum penalty for an additional missed trip is $10,000. For a worst case scenario, the impact for classifying a short turned train as a late trip or as a missed trip is quite similar for both assumptions. However, the analysis above is uncertain for two reasons. First, we can not define short turning with certainty as either a late or a missed trip because there is no information to support that classification. Second, the behavior of the system is completely unknown, and there is no data to estimate the average number of late and missed trips based on a statistical analysis. For example, let us assume that on average the number of missed trips is below the base, but the number of late trips is above the base. If short turning is considered to be a missed trip, the financial impact will not be as severe as if it is considered as a late trip, under that assumption. Therefore, the only conclusion that can be drawn from this analysis is that any short turned train will represent a reduction in revenue; therefore, the contractor is likely to avoid using it during a disruption, even though it may improve service quality as perceived by passengers. For the purpose of this research, short turning will be included in the analysis to compare the additional savings when included as a control strategy in combination with holding.

4.2 Description of Methodology

The optimization model introduced in Chapter 2 was used to estimate the impact of the contract terms on control decisions. Specifically, the model was used to determine both the optimal set of control strategies and the hypothetical set of control strategies given the Tren Urbano contract terms. Equation 4-1 was added to the model formulation to simulate the contract term restrictions since only peak period disruptions were analyzed. In addition to the control actions, the model also gives the total passenger waiting time resulting from the control actions. The holding times obtained from the model are then used as input to the analytical model. With the holding times that minimize the passenger waiting time, the headway sequences for all the stations are estimated, assuming no other disturbances occur during that period.

Recovery at terminals would also be affected by the contract terms structure. Recovery times at the terminals are used to help trains to depart on schedule. For example, in the case of Tren Urbano, the recovery time during the AM Peak is 4 minutes, and the minimum recovery time is 2 minutes (Siemens Transit Team, 1999). This value corresponds to the minimum time for the operator to change ends (of the train) and be ready to depart. If a train arrives late at a terminal, it can recover two minutes of delay with the minimum recovery time. In a situation where there are two late trains and both headways are 8-minutes, based on the contract terms, the lead train would recover 2 minutes at the terminal and the headways would then be 6-minutes and 8-minutes. The lead train would be on-time when it arrives at the next terminal because it would be 2 minutes off-schedule, which is the maximum allowable deviation from schedule according to the contract terms. On the other hand, if the priority is to minimize the headway variance, the first train would recover one minute at the terminal while the second train would have the minimum recovery time and recover 2 minutes. In this case the headway sequence would be 7-minutes for the following trips for each train. However, both trains would still be late for their next trip, increasing the number of late trips and consequently, the financial impact of the disruption. Considering the service quality impact of both actions, the average waiting time for the 6-8 headway sequence is 3.6 minutes; for the 7-7 headway sequence the average waiting time is 3.5 minutes. There is a reduction of about 4% in waiting time when the recovery time is used to even out the headways. In addition to the recovery time adjustments, we also held trains ahead of the blockage, which were not held as part of the optimization model, at the terminal. Even though we included two trains ahead of the blockage as part of the control set of trains in the optimization model, there were situations where no control strategy was recommended for these trains. The model was developed to minimize the passenger waiting time, and in some of the scenarios analyzed here, the trains had already passed the optimal holding locations, and presumably holding these trains at other stations before the terminal would result in waiting time increases. Therefore, to reduce the headway variation, these trains were held at the first terminal they arrive at immediately after the disruption. In the analytical model, a set of equations is used to estimate the impact of these control decisions in the disruption analysis as a function of four components: On-platform waiting time, active/passive holding delay and passenger left additional waiting time. Each of these is discussed below.

4.2.1 On-platform waiting time

The holding times are obtained from the model developed by Shen (2000). Once this information is available, the headway sequence at each station is estimated for the first two round trips of the impact set of trains, which is the equivalent to the AM peak period. The first reason to use only two round trips is because the AM peak is 2 hours long and after the AM peak period the service changes to 8-minutes headways. Some trains will be removed from the system, changing the original assumptions made on the impact set of trains. Second, it is not reasonable to try to predict the behavior of the system more than two hours ahead, given that other events can affect the performance of the system.

The on-platform waiting time for each station is estimated from this headway sequence. For a station with no holding (passive or active), the average waiting time is calculated using the following equation:

$$WT_k = \left(\frac{H_{mean}}{2}\right) * \left(1 + \frac{Variance_H}{H_{mean}^2}\right) \qquad (4\text{-}3)$$

where:

WT_k = mean waiting time at station k, in minutes

H_{mean} = headway sequence average

$Variance_H$ = variance of the headway sequence

This equation was introduced in chapter 1; here the subscript *k* is used to identify on-board waiting time at a particular station. This equation reflects the critical importance of regular headways. If the headway coefficient of variation increases, the average waiting time increases. This waiting time equation is valid for high frequency services, where passenger arrivals are randomly distributed and the arrival rate can be assumed constant for the time period under analysis (Welding, 1957; Turnquist et al, 1980). To estimate the total passenger waiting time at the station in pass-minutes units, WT_k is multiplied by the total of passengers that arrive at the station during the two round trips corresponding to the impact set of trains. The impact set of trains is the total trains that are affected by the blockage plus the trains that are controlled. The *Total* WT_k is calculated with the following equation:

$$Total\ WT_k = WT_k * \sum_{all\ i} H_{i,k} * A_k \tag{4-4}$$

In the case of stations where trains are held, this equation can not be used because it overestimates the passenger waiting times. The headway definition used in equation 4-3 refers to the departing headway of trains. However, in the case of a holding station, the departing headway includes the holding time plus the time between the preceding train departure and the current train arrival plus normal dwell. Consequently, the passenger waiting time includes the passengers that arrive during holding; however, these passengers indeed have zero waiting time, i.e. the train is at the platform when they arrive. The time between the departure and arrival of trains plus the dwell time, $h_{i,k}$, is used to estimate the station waiting time. Hence, the equation to estimate the waiting time at holding locations (in pass-minutes) is the following:

$$Total\ WT_k = \frac{A_k}{2} * \sum_{all\ i} h_{i,k}^2 \tag{4-5}$$

The *Station WT* is given by the following equation:

$$Station\ WT = \sum_{all\ k} Total\ WT_k \tag{4-6}$$

4.2.2 On-board delay

The second component of the total passenger waiting time in the system is the passive/active delay. The passive delay refers to the additional wait for passengers boarding trains directly affected by the blockage. These trains are forced to hold at a particular station behind the blockage until the blockage is cleared. This value is a constant that depends on the length of the blockage, and does not change with variations to the control strategies in front of the blockage. The only factor that changes the value of the passive holding time is if short turning is used, and the short-turned train is part of the impact set in the holding-only situation. For example, if there is a 10-minute disruption, and the minimum headway is 2 minutes, there will be 4 trains behind the blockage that will be held until the blockage is cleared. If any of those trains were short-turned, the passive holding value would be reduced because that train would not have to sit at a station until the blockage is cleared. Certainly, short turning that train will have other impacts on waiting time including: reductions to headway in the reverse direction of travel, increase in waiting time in its original direction of travel, and the additional waiting time to passengers who have to alight from the train at the station before the crossover maneuver.

The active holding waiting time depends on the amount of holding recommended in order to minimize the disruption impact on waiting time. The equation used to estimate the on-board delay for both the active and passive holding is:

$$Total\ On-board\ delay = \sum_{\substack{all\ i \\ all\ k}} U^{iw} * \left[\frac{A_k}{2} * ht_{i,k}^2 + (l_{i,k} - A_k * ht_{i,k}) ht_{i,k} \right] \qquad (4\text{-}7)$$

The first part of the equation represents the on-board delay for passengers arriving during holding, while the second term refers to the on-board delay for those already on-board when holding started. U^{iw} is a weighting factor to reflect the fact that passengers may perceive in-vehicle waiting time to be less onerous than platform waiting time. For the on-board delay caused by active holding, this value will be assumed to be 0.5, which is a reasonable value according to previous research by Abdel-Aty, Kitamura and Jovanis (1995). Nevertheless, since passive holding results from the disruption and no matter how passengers perceive waiting on board they are subject to this additional delay, U^{iw} will be assumed to be 1.0. On board delay caused by passive holding is included in the analysis because, as mentioned earlier, the short turned train affects this value if the short turned train is part of the impact set of trains behind the blockage, which may be the case here.

4.2.3 Additional Waiting Time for Passengers Left Behind

The third component of the total waiting time in the system is the additional waiting time experienced by passenger left at a station by an overcrowded train. In the case of short turning, it also includes the passengers who are forced to alight from the train as well as the passengers already waiting at the platform since the departure of the previous train. The equation to estimate the additional waiting time is:

$$Add.WT_{pass\ left} = \sum_{\substack{all\ i \\ all\ k}} p_{i,k} * h_{i+1,k} \qquad (4\text{-}8)$$

The number of passenger left behind, which is needed to estimate the additional waiting time, is obtained from the optimization model results.

4.2.4 Total Waiting Time

The total waiting time of the system will be the sum of all the three components discussed above. WT_{System} and $WT_{Average}$ are calculated to compare the savings in waiting time between control strategies. Also, the number of additional late trains resulting from the optimal control actions will be estimated in order to compare the financial impact versus the service quality improvements of the optimal strategy versus the hypothetical Tren Urbano strategy.

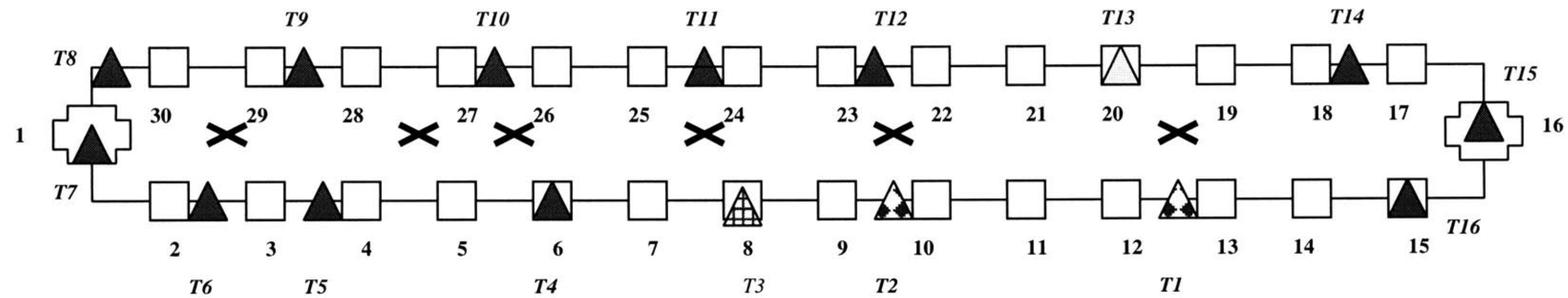
4.3 Problem Description

Disruptions at two different locations were analyzed: Centro Médico and Jardines. These two locations were chosen to represent a disruption at approximately the middle of the alignment and another close to the beginning of the line. Both disruptions occur during the AM peak period in the travel direction towards San Juan, which is expected to be the peak direction of travel during the morning. The aim of using these locations and the AM peak period is to analyze potential worst case scenarios of a disruption, so the impact of decisions are critical and the importance of developing contract terms that encourage the provision of high service quality is emphasized. Disruption durations of 10-minutes and 20-minutes are analyzed at both locations. The disruptions will be identified as CM-10, CM-20, J-10 and J-20. It is assumed that the disruption begins at the moment the train affected is ready to depart from the station. Figures 4-1 and 4-2 are schematic representations of the line including the stations, the crossover track locations and the train positions at the moment of the disruption for Centro Médico and Jardines respectively.

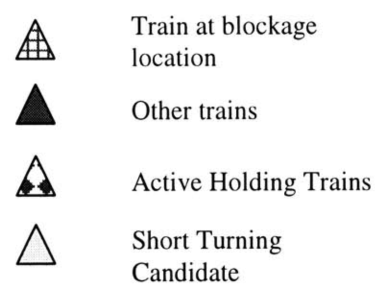
4.3.1 Impact Set

In the Centro Médico disruption, T3 is the disrupted train and T1 and T2 are the trains considered for holding with the optimization model determining the holding times. For CM-10, T4 to T8 are included in the impact set, since these are the trains that are affected by the passive holding. The impact set is extended in the case of CM-20 and includes trains up to and including T14. T13 is the potential candidate for short turning, and would be short-turned at the crossover between stations 9 and 10 (Cupey and Río Piedras).

Figure 4-1 Tren Urbano Schematic – Centro Médico Disruption

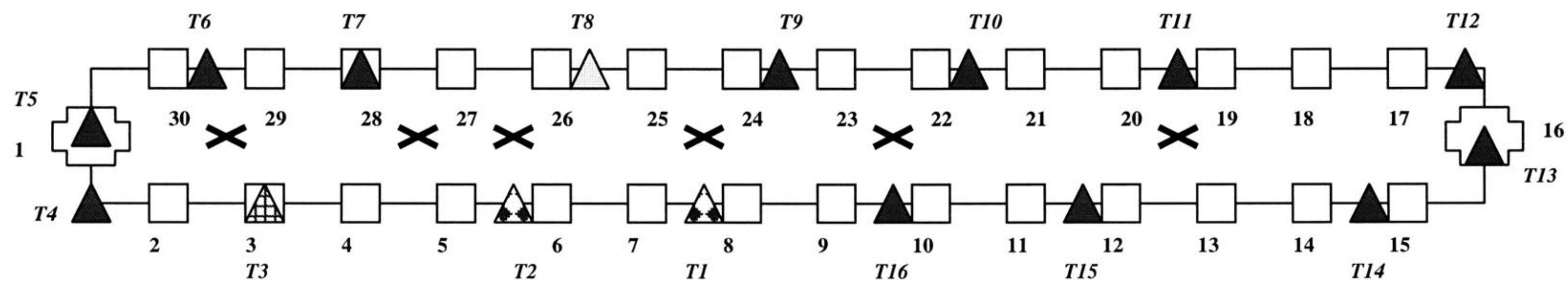


Station	Name	Station	Name
1	Bayamón	9,23	Cupey (Villa Nevárez)
2,30	Deportivo	10,22	Río Piedras
3,29	Jardines (Río Bayamón)[19]	11,21	Universidad (UPR)
4,28	Torrimar	12,20	Piñero (Centro Judicial)
5,27	Martínez Nadal (Las Lomas)	13,19	Domenech
6,26	Las Lomas (San Alfonso)	14,18	Roosevelt (Hato Rey)
7,25	San Francisco (De Diego)	15,17	Hato Rey (Nuevo Centro)
8,24	Centro Médico	16	Sagrado Corazón

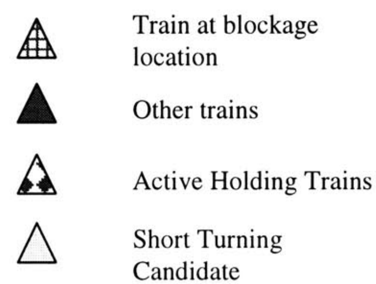


[19] The names in parenthesis correspond to former names of the stations

Figure 4-2 Tren Urbano Schematic – Jardines Disruption



Station	Name	Station	Name
1	Bayamón	9,23	Cupey (Villa Nevárez)
2,30	Deportivo	10,22	Río Piedras
3,29	Jardines (Río Bayamón)	11,21	Universidad (UPR)
4,28	Torrimar	12,20	Piñero (Centro Judicial)
5,27	Martínez Nadal (Las Lomas)	13,19	Domenech
6,26	Las Lomas (San Alfonso)	14,18	Roosevelt (Hato Rey)
7,25	San Francisco (De Diego)	15,17	Hato Rey (Nuevo Centro)
8,24	Centro Médico	16	Sagrado Corazón



For the Jardines disruption, T3 is again the disrupted train, and T1 and T2 are also considered for holding. The impact set in the J-10 disruption includes up to T9, given that T8 is a candidate for short turning. T8 can be short-turned between Martínez Nadal and Las Lomas stations. The impact set is extended to T14 for the analysis of J-20. Short turning a second train, T9, was also considered in J-20 disruption for two reasons. First, because of the length of the disruption, and second, because short turning a second train will not interfere with the train movements after the disruption is cleared. In the case of CM-20, short turning a second train was not considered because short turning T14 may interfere with the operation of T3 after the disruption is cleared, given the location of the T14 relative to the crossover at the moment of the disruption.

4.3.2 Evaluation Time Window

The time to return to normal 'schedule' operation for a 10-minute disruption, assuming that the trains can recover 2 minutes at the terminals, is equivalent to 2.5 roundtrips. Given that each round trip is 64-minutes long, the time required to recover would be approximately 2.5 hours. However, given that the peak period is 2 hours, the waiting time impacts will be estimated based on 2 round trips only. The same principle is applied to the 20-minute disruption. Even though the required amount of time to recover is approximately 5 hours (or the equivalent of 5 round trips), only 2 round trips are used to estimate the waiting time. The use of 2 round trips implies that the disruption occurs at the beginning of the peak period – again a worst case.

After the peak period, the service headways are increased to 8 minutes. This means that at the end of the peak period some trains are pulled out of service and returned to the yards (or stored at the terminals) until the next peak period. Even though the total impact of a disruption could be analyzed, the formulation would become more complicated given the changes in passenger arrival rates at each station and the change in headway between time periods. To simplify the analysis, only the peak period effects of control strategies and recovery decisions are analyzed. This assumption is valid given that the most significant impact on the passenger waiting time comes during the first round trip. The control strategies are implemented immediately after the disruption; therefore the effects of control after the disruption can be estimated simply by calculating the passenger waiting times using the headway sequences after holding until the trains reach the terminal. Passengers left behind and the active/passive passenger delay components are estimated by using the headway sequences from the first round trip. The second trip is in the travel direction towards Bayamón, where demand levels are lower than in the travel direction towards San Juan; therefore, no passengers are left after trains complete their first trip. The second round trip is used to determine how the different dispatching strategies affect waiting time given that recovery times are used in the optimal solution to achieve even headways, and in the case of scheduled operation these are used to get back on schedule.

4.3.3 Input Data

The following data were used as input for both the optimization model and the analytical model:

1. Dwell time: in the case of Tren Urbano, there is obviously no data yet to determine the train dwell times at the stations. In the absence of this, the dwell time is set to 30 seconds, which is the value that has been used to determine the round trip time in operations planning. In reality, minimum dwell time is a function of passenger boardings and alightings and it will likely vary depending on the headway. If a particular headway is large, the dwell time will also be large because there will be more boardings and alightings, and vice versa. The 30 seconds figure is probably conservative.
2. Train location: for both scenarios, the last station departure of each train was estimated based on the running times between stations and the location of the trains at the moment of the disruption.
3. Passenger arrival rates and alighting fraction: the ridership data used was obtained from forecasts by Cambridge Systematics, Inc for Tren Urbano (various fax memos and email from Bill Craven, January, March & December 1999). Cambridge Systematics developed a model to estimate the boardings and alightings at each station. For the purpose of this analysis, only the AM peak

period data are used since this is when the highest demand occurs and thus the impacts of a disruption are most critical at this time period. The forecast demand figures correspond to 2010 demand; therefore, the scenarios presented here should not represent a disruption during the early days of operation. However, it is reasonable to use these demand forecasts, given that they represent the expected ridership after the system has reached steady state operations and demand.

The demand forecasts include estimated total alightings and boardings per station and direction of travel for a one-hour period. To estimate the alighting fraction, the load at each station was calculated using the following equation:

$$Load_k = Load_{k-1} + Boardings_k - Alightings_k \qquad (4\text{-}9)$$

Then, the alighting fraction was calculated as the ratio of the alightings and the load for each station,

$$A_k = Alightings_k \,/\, Load_{k-1} \qquad (4\text{-}10)$$

Appendix B includes a table with loads, alighting fractions and arrival rates for each station.

4. Normal loads and current load: this data was also obtained from the ridership data mentioned above, using equation (4-9). In this analysis, the current load corresponds to the normal load at the last departure station for each train.

5. Train running time: train running time was obtained from the MATRA simulation trials from Jan 98 and July 98 as reported in two documents submitted to Tren Urbano by the contractor (see Appendix C). The first document justifies the additional cars needed given the change to round trip time caused by the addition of two stations after the FEIS submittal (Universidad and Domenech stations) and the relocation of Cupey station. The second document is the Operations and Maintenance Plan (October 1999).

6. Minimum headway: 2 minutes, as specified in the contractor's input data.

7. Short-turning time between Cupey-Río Piedras and Las Lomas-Martínez Nadal: the short-turning time was estimated using the crossover tracks distance from the stations, the speed at the given segment, and assuming 6 minutes to switch directions (including the time needed for the driver to move between train ends). The crossover locations including the distance from the platforms are included in Appendix D. The speed between stations is included in Appendix C. The time to short-turn either after the Río Piedras station or after the Martínez Nadal station was estimated to be 7 minutes.
8. Passengers left behind, loads at holding stations and holding times: these values used in the analytical model are obtained from the optimization model results.

4.3.4 Scenarios

Each disruption situation was analyzed under four scenarios: do-nothing, optimal solutions (holding only and holding combined with short turning), and hypothetical Tren Urbano scenario, as defined below.

1. Do-nothing: the do-nothing scenario serves as a base to estimate the impact of a disruption on passenger waiting time and to assess the savings from any control strategy.
2. Optimal solution, holding only: using the optimization model, holding times are estimated for the control set of trains. The control set of trains for each disruption consists of the 2 trains immediately ahead of the blockage.
3. Optimal solution, short-turning: in this case, short turning is combined with holding. However, the short-turning train and the short-turning location are pre-selected, and they are not a decision of the model. CM-10 is the only scenario in which short turning is not considered. At the moment of the disruption, the potential candidate for short turning is 3.7 minutes away from the Río Piedras station, which is the last station the train stops at before short turning. The time to change directions and to arrive at Río Piedras station (towards San Juan) is more than 7 minutes. That means that it would require more than 10 minutes to complete the short turning maneuver for this train. In this case short turning

might cause additional delays to the trains behind the blockage given the amount of time it takes to complete. As Shen (2000) concluded in his research, short turning may not be beneficial in the case of a shorter than predicted disruption duration. In addition, since the disruption occurs in the middle of the alignment, many of the high demand stations are before the Río Piedras station in the San Juan direction; therefore short turning would inconvenience more passengers in the Bayamón direction of travel than would benefit in the opposite direction.

4. Hypothetical Tren Urbano scenario: in this case, the train ahead of the blockage is restricted to a maximum total holding time of 2 minutes, which is the maximum deviation from schedule without incurring late train penalties. Basically, compared with the do-nothing case, the only difference is that the train ahead of the blockage is held for 2 minutes.

The optimization model decides how long trains should be held and at which stations. It was programmed to determine holding times up to Hato Rey station, which is the station before the terminal station in the direction towards San Juan. Trains ahead of the blockage are held at the terminal if the optimization model did not recommended any holding before arriving at the terminal to minimize the headway variance. Trains behind the blockage use the minimum recovery time at the terminal to catch up with the schedule.

The optimization and analytical models include other important assumptions in the formulation that need to be recognized. First, the reaction to being dumped from a train during short turning is no included. In addition, many of the parameters used in the formulation, such as dwell time, arrival rates, and running times, among others, are assumed to be deterministic. Finally, on-board delay was considered less onerous than on-platform waiting time, with a weighting factor of 0.5.

4.4 Results

4.4.1 Centro Médico – 10 minute disruption (CM-10)

The control strategies obtained from the optimization model are summarized in Table 4-1. The holding-only solution includes holding T2 for 4-minutes at the Río Piedras station, which is the first station the train arrives at after the disruption. The optimization model does not hold T1, because that train has already passed the stations with high demand at the moment of the disruption. As part of the dispatching control, train T1 is held at the terminal for two minutes to minimize the headway variance. The holding only strategy analyzed here represents a lower bound in terms of minimizing passenger waiting time. For the hypothetical Tren Urbano scenario, train T2 was held at Río Piedras for 2 minutes. Table 4-2 presents the headway sequence for the eight trains in the impact set for the subsequent three one-way trips for the do-nothing, holding-only and hypothetical Tren Urbano strategies at the last station before the terminus in each direction.

Table 4-1 CM-10: Control Strategies

Strategy	Actions
Holding Only	Hold T2, 4-minutes @ Río Piedras Hold T1, 2-minutes @ Sagrado Corazón
Tren Urbano Solution	Hold T2, 2-minutes @ Río Piedras

Table 4-2 CM-10: Headway Sequence

1st Trip – Hato Rey (to SC)			
Train #	Do-Nothing	Holding Only	TU Scenario
1	4	4	4
2	4	8	6
3	14	10	12
4	2	2	2
5	2	2	2
6	2	2	2
7	2	2	2
8	2	2	2
2nd Trip – Deportivo (to BC)			
Train #	Do-Nothing	Holding Only	TU Scenario
1	4	6	4
2	4	6	6
3	12	8	10
4	2	2	2
5	2	2	2
6	2	2	2
7	2	2	2
8	4	4	4
3rd Trip – Hato Rey (to SC)			
Train #	Do-Nothing	Holding Only	TU Scenario
1	4	6	4
2	4	6	6
3	10	6	8
4	2	2	2
5	2	2	2
6	2	2	2
7	4	4	4
8	4	4	4

Table 4-3 CM-10: Analytical Method Results

	Do-nothing	Optimal Holding	Contract Holding
Station WT	30332	25195 (16.9%)	27121 (10.6%)
Passive Holding	12352	12352	12352
Active Holding	0	1041	458
Left Behind WT	196	60 (69.4%)	128 (34.7%)
Total WT	42880	38648 (9.9%)	40059 (6.6%)
Average WT	4.25	3.83 (9.9%)	3.97 (6.6%)
# late trains	12	15	12

Table 4-4 CM-10: Comparison between Optimal Solution (Holding Only) vs. Tren Urbano Solution

Measure	Savings
Station WT	7.1%
Active Holding	127% increase
Left Behind WT	53.1%
Total WT	3.5%

Tables 4-3 and 4-4 summarize the analytical model results. In Table 4-3, the numbers in parenthesis represent the savings from implementing the optimal and the hypothetical Tren Urbano strategies respectively compared with the do-nothing scenario. The saving in the total passenger waiting time obtained from the holding-only solution is almost 10% when compared with the do-nothing solution. Comparing the optimal solution with the hypothetical Tren Urbano solution (Table 4-4), there is a reduction of 3.5% in total waiting time from the optimal holding strategy. The station waiting time is reduced by almost 17% in the optimal solution compared with almost 11% in the hypothetical Tren Urbano. This reduction of about 7% comparing the holding-only vs. the hypothetical Tren Urbano strategy is the result of the reduction in headway variability shown in Table 4-2. The active holding in the optimal solution is twice that in the hypothetical Tren Urbano solution; however, it represents only about 2% of the total waiting time. Even though active holding for the optimal solution is higher than for the hypothetical Tren Urbano solution, the effect on the total waiting time is outweighed by the waiting time savings from the other components.

The optimal solution also gives a significant reduction in the savings related to passengers left behind. Even though the optimal solution does not completely avoid leaving passengers on the platform, it does reduce it by almost 70% compared with the do-nothing scenario and by more than half when compared with the hypothetical Tren Urbano solution. On the other hand, the most significant disadvantage of implementing the optimal solution with respect to the contract terms is that 3 additional trains are off-schedule. In the worst case scenario, this could represent an additional penalty of $9,000 under the current contract terms. This is the basic reason why the optimal solution would probably not be implemented in this disruption scenario.

4.4.2 Centro Médico – 20 minute disruption (CM-20)

In the CM-20 disruption, the optimal holding-only solution includes holding train T2 for 8-minutes at Río Piedras, and as in CM-10, T1 was held 4 minutes at Sagrado Corazón (see Table 4-5). The optimal short-turning solution consists of short-turning train T13 in front of T4 to reduce the gap from 24 minutes to 12 minutes. T13 is also held for 1-minute at the Río Piedras station after short turning. T1 is held 2 minutes and T2 is held 4 minutes at the terminal (Sagrado Corazón) to minimize the headway variance. Table 4-6 shows the headway sequences for each scenario and Tables 4-7 through 4-10 summarize the results for this disruption.

Table 4-5 CM-20 disruption: Control Strategies

Strategy	Actions
Holding-only	Hold T2, 8-minute @ Río Piedras Hold T1, 4-minute @ Sagrado Corazón
Short Turning & Holding	Short-turn T13 in from station 22 to station 10 (Río Piedras) Hold T13, 1-minute @ Río Piedras Hold T1, 2-minute @ Sagrado Corazón Hold T2, 4-minute @ Sagrado Corazón
Tren Urbano Solution	Hold T2, 2-minute @ Río Piedras

The results in Table 4-7 show significant savings from the optimal control strategies compared to the Tren Urbano hypothetical solution. In this case, the contractor's control decisions are likely to be quite different from the optimal control actions that could be applied in such a disruption. The contractor's likely actions are limited to holding a train for only 2-minutes; during a long disruption, that holding time is not enough to dissipate the effect of the large gap between the blocked train and the train immediately ahead of it. The Tren Urbano hypothetical solution gives a total saving of 6%, less than half the savings from the optimal solutions which range from 17% to 23%.

Table 4-6 CM-20 disruption: Headway Sequences (1st Trip)

1st Trip – Hato Rey (to SC)				
Train #	**Do-Nothing**	**Holding Only**	**Short Turning**	**TU Scenario**
1	4	4	4	4
2	4	12	4	6
3	24	16	12	22
4	2	2	2	2
5	2	2	2	2
6	2	2	2	2
7	2	2	2	2
8	2	2	2	2
9	2	2	2	2
10	2	2	2	2
11	2	2	2	2
12	2	2	4	2
13	2	2	12[20]	2
14	4	4	4	4
2nd Trip – Complejo (to BC)				
Train #	**Do-Nothing**	**Holding Only**	**Short Turning**	**TU Scenario**
1	4	8	6	4
2	4	8	6	6
3	22	14	12	20
4	2	2	2	2
5	2	2	2	2
6	2	2	2	2
7	2	2	2	2
8	2	2	2	2
9	2	2	2	2
10	2	2	2	2
11	2	2	4	2
12	2	2	4	2
13	4	4	6[21]	4
14	4	4	4	4
3rd Trip – Hato Rey (to SC)				
Train #	**Do-Nothing**	**Holding Only**	**Short Turning**	**TU Scenario**
1	4	8	6	4
2	4	8	6	6
3	20	12	10	18
4	2	2	2	2
5	2	2	2	2
6	2	2	2	2
7	2	2	2	2
8	2	2	2	2
9	2	2	2	2
10	2	2	4	2
11	2	2	4	2
12	4	4	4	4
13	4	4	6	4
14	4	4	4	4

[20] T13 is located between T2 and T3 in the short turning scenario.

[21] T13 is located between T2 and T3 in the short turning scenario.

Table 4-7 CM-20: Analytical Model Results

	Do-nothing	Holding Only	Contract	Short-turning
Station WT	94114	68701 (27%)	85466 (9.2%)	61606 (34.5%)
Passive Holding	44203	44203	44203	44203
Active Holding	0	2255	458	746
Left Behind WT	1078	726 (32.7%)	962 (10.8%)	1428 (24.5%)
Total WT	139395	115885 (16.9%)	131090 (6.0%)	107982 (22.5%)
Average WT	5.75	4.78 (16.9%)	5.41 (6.0%)	4.46 (22.5%)
# late trains	28	33	28	47

The optimal (holding-only) solution provides significant savings in terms of station waiting time, left behind waiting time and the total waiting time compared with the do-nothing scenario. The active holding time however is quite high; up to 5 times the active holding time with the other two strategies (see Table 4-9). However, as in CM-10, it represents only a small fraction of the total waiting time (about 2%). The main contribution of the holding-only scenario is in the savings in station waiting time, which is the combination of both holding actions and recovery decisions.

The short turning scenario provides the best solution in terms of total waiting time savings however at the cost of increasing the number of passengers of left behind and their waiting time, even though the number of passengers left is less than in the do-nothing case (see Table 4-8). This is the result of the higher on-platform waiting for passengers that are forced to alight from the short-turned train and those that were already on the platform waiting to board that particular train. As in the case of active holding, the passengers left waiting time is just a small fraction of the total waiting time; in this case about 1%. The main impact of this strategy in total waiting time is caused by the considerable reduction to headway irregularity as shown in Table 4-6.

Table 4-8 CM-20 disruption: Passenger Left Behind

Scenario	Cupey (to SC)		Río Piedras (to SC)		Piñero (to SC)		Río Piedras (to Bayamón)		Total Passengers Left Behind
Do-nothing	T3	176	T3	324	T3	39	T13	0	539
Holding Only	T3	176	T3	187	T3	0	T13	0	363
Short turning	T3	176	T3	119	T3	0	T13	177	472
Tren Urbano Sln.	T3	176	T3	290	T3	15	T13	0	481

Table 4-9 CM-20 disruption: Comparison between Optimal Solution (Holding Only and Short Turning) vs. TU Solution

Measure	Savings	
	Holding Only	Short-turning
Station WT	19.6%	27.9%
Active Holding	(391.8%)	(62.6%)
Load Left WT	24.5	(48.4%)
Total WT	11.6%	17.6%

Table 4-10 CM-20 disruption: Comparison Short Turning w/Holding vs. Holding-only

Measure	Savings
Station WT	10.3%
Active Holding	66.9%
Left Behind WT	(96.7 %)
Total WT	6.8%

Comparing both optimal solutions with the Tren Urbano hypothetical solution (Table 4-9), the savings in total waiting time range from about 12% to 18%. These are significant savings over the hypothetical Tren Urbano solution. The active holding and left behind waiting times are increased with the optimal strategies; however, their contribution to waiting time is not nearly enough to make them less effective overall than the Tren Urbano hypothetical solution.

Table 4-10 compares both optimal solutions: short turning w/holding versus holding-only. The benefits of short turning are greater than holding alone with a 7% reduction in total waiting time. However, although short turning obviously reduces considerably the total waiting time because it reduces the headway variance, there is a substantial difference on the impact to the other waiting time components between these strategies. The holding-only solution has an active holding waiting time about 67% higher than for short turning. On the other hand, the left behind waiting time for the short turning scenario is twice that for holding only. In addition to considering the alternative that reduces total waiting time, the controller can decide between minimizing the effects of left behind waiting time versus active holding waiting time. However, as mentioned above, since these two components are just a small fraction of the total passenger waiting time, their differences in both scenarios are not enough to affect substantially the total savings in passenger waiting time from short turning trains.

In terms of the financial impacts, the short turning solution is the worst option for the contractor. The number of late trains resulting from the optimal control action increased by 19. This means that the maximum financial impact is \$750 x 19 = \$14,250, that is without including the trains behind the blockage that are also late as a result of the disruption. The holding-only solution would be financially preferable to the short turning solution, given that the impact is \$3750. That is about 74% less than the short turning solution financial penalty.

4.4.3 Jardines – 10 minute disruption (J-10)

For the Jardines disruption, holding only and short turning are again considered as the optimal solution scenarios, and as in the previous cases, do-nothing and Tren Urbano solution were also analyzed. Contrary to CM-10, short turning can be considered in this case, given that the potential short turning candidate is about to arrive at the station before the crossover tracks when the disruption occurs. The short turned train would arrive at the Las Lomas (San Alfonso) station platform travelling towards San Juan 7.5 minutes after the disruption occurs. In this case, it is reasonable to consider short turning as part of the control strategies, since it takes several minutes less than the assumed disruption duration. In the event that the disruption is shorter than expected, the impact would not be as negative as it might have been in the Centro Médico disruption.

Control strategies are summarized in Table 4-11. The holding only solution set of control strategies includes holding train T1 at Cupey for 2 minutes. Cupey is the second station T1 reaches after the disruption. Train T2 is held at Las Lomas, the first station it arrives at after the disruption, for 6 minutes. The short-turning solution set of control strategies includes short turning T8 in front of the blocked train reducing the disrupted headway from 14 minutes to 7.5 minutes. No additional control action is required for T8. T7 is held for 2-minute at the Bayamón station to reduce the gap between T7 and T9 after T8 is short turned. T2 is held for one minute at Sagrado Corazón as a dispatching strategy. The hypothetical Tren Urbano strategy consists of holding train T2 for 2-minutes at Las Lomas station.

Table 4-10 J-10: Control Strategies

Strategy	Actions
Holding Only	Hold T1, 2 minute @ Cupey Hold T2, 6-minutes @ Las Lomas
Tren Urbano Solution	Hold T2, 2-minutes @ Río Piedras
Short turning	Short turn T8 from station 26 to 6 (Las Lomas) Hold T7, 2-minutes @ Bayamón Hold T2, 1-minute @ Sagrado Corazón

Table 4-12 J-10: Headway Sequence

1st Trip – Hato Rey (to SC)				
Train #	Do-Nothing	Holding Only	Short Turning	TU Scenario
1	4	6	4	4
2	4	8	4	6
3	14	8	7.5	12
4	2	2	2	2
5	2	2	2	2
6	2	2	2	2
7	2	2	4	2
8	2	2	6.5[22]	2
9	4	4	4	4

[22] T8 is located between T2 and T3 in the short turning solution

Table 4-12 J-10: Headway Sequence (cont.)

2nd Trip – Deportivo (to BC)				
Train #	Do-Nothing	Holding Only	Short Turning	TU Scenario
1	4	6	4	4
2	4	7	5	6
3	12	7	6	10
4	2	2	2	2
5	2	2	2	2
6	2	2	4	2
7	2	2	4	2
8	4	4	5[23]	4
9	4	4	4	4
3rd Trip – Hato Rey (to SC)				
Train #	Do-Nothing	Holding Only	Short Turning	TU Scenario
1	4	6	4	4
2	4	6	4	6
3	10	6	5	8
4	2	2	2	2
5	2	2	4	2
6	2	2	4	2
7	4	4	4	4
8	4	4	5	4
9	4	4	4	4

Table 4-13 J-10 disruption: Analytical Model Results

	Do-nothing	Optimal	Contract	Short Turning
Station WT	39794.3	32999 (17.1%)	36184 (9.1%)	30187 (24.1%)
P. Holding	9531	9531	9531	9531
A. Holding	0.0	1807	385	326
Left Behind WT	604.0	0 (100%)	394 (34.8%)	580 (4.0%)
Total WT	49929	44337 (11.2%)	46493 (6.9%)	40624 (18.6%)
Average WT	3.41	3.03 (11.2%)	3.18 (6.9%)	2.78 (18.6%)
# late trains	13	16	13	21

[23] T8 is located between T2 and T3 in the short turning solution

Table 4-14 J-10 disruption: Comparison between Optimal Solution (Holding Only and Short Turning) vs. Tren Urbano Solution

Measure	Savings	
	Holding Only	Short-turning
Station WT	8.8%	16.6%
Active Holding	(369.8%)	15.2%
Load Left WT	100.0%	(47.2%)
Total WT	4.6%	12.6%

Table 4-15 J-10 disruption: Comparison Short Turning w/Holding vs. Holding-only

Measure	Savings
Station WT	8.5%
Active Holding	81.9%
Load Left WT	-
Total WT	8.4%

Table 4-12 shows the resulting headway sequences and Tables 4-13 through 4-15 summarize the results of the analytical model. The optimal control strategies can produce benefits in the range of about 11%-19% for the total waiting time savings compared with the hypothetical Tren Urbano solution impact of about 7%. The main component of total waiting time, the station waiting time, produced savings in the range of 17% to 24% when applying the optimal solutions, compared with the 9% savings from using the hypothetical Tren Urbano control strategy.

The holding-only solution has a considerably higher active holding waiting time compared with the other two scenarios, up to 5 times the active holding from the Tren Urbano hypothetical solution. However, the same pattern observed in the previous disruption cases is repeated here: this is only a small fraction of the total waiting time. The disbenefit caused by active holding is more than compensated by the significant reduction to station waiting time (17%) and the fact that no passengers are left behind.

On the other hand, the negative aspect of the short-turning solution is in the number of passenger left behind. Although passenger left waiting time is only 4% less than the do-nothing case, its contribution to the total waiting time is so small that the station waiting time savings are more than enough to counteract the negative effect it has on total waiting time. The station waiting time is reduced by about 24% in this scenario.

Comparing the optimal solutions with the hypothetical Tren Urbano solution in terms of service quality, the improvements are in the range of 5% and 12% for the holding-only and short turning scenarios, respectively. Short turning compared with the do-nothing scenario represents an 8% saving in total waiting time, and significantly reduces the active holding. Nevertheless, the financial impact of the short-turning solution is higher than the financial impact of the holding-only solution. The number of late trips is increased by 7 compared with the hypothetical Tren Urbano solution, which could result in a short turning penalty of as much as $9,000.

4.4.4 Jardines – 20 minutes disruption (J-20)

The control strategies are summarized in Table 4-16. The holding-only control strategy includes holding trains at multiple locations. T1 is held at Centro Médico (4 minutes), Cupey (2 minutes) and Río Piedras (2 minutes). T2 is held at Las Lomas (8 minutes) and San Francisco (2 minutes).

Two short turning scenarios were analyzed in this case because of the length of the disruption. The first short turning control strategy include short-turning T8 in front of the blockage and holding it at Las Lomas (5.3 minutes) and Cupey (4 minutes). In addition, T2 is held at Las Lomas (2.7 minutes) and at San Francisco (1.3 minutes). T1 is held at the terminal (Sagrado Corazón) for 2 minutes. In the second short turning scenario, both T8 and T9 are short turned at Las Lomas. T8 is held at San Francisco station for 1.3 minutes and T9 is held at Las Lomas station for 5.3 minutes. In addition, both T1 and T2 are held at Sagrado Corazón for 1 and 2 minutes, respectively.

The headway sequences for each scenario are shown in Table 4-17 and the analytical model results are summarized in Tables 4-18 through 4-20.

Table 4-16 J-20: Control Strategies

Strategy	Actions
Holding	Hold T1, 4-minute @ Centro Médico 2-minute @ Cupey 2-minute @ Río Piedras Hold T2, 8-minute @ Las Lomas 2-minute @ San Francisco
Short Turning & Holding I	Short-turn T8 from station 26 to station 6 (Las Lomas) Hold T8, 5.3-minute @ Las Lomas 4-minute @ Cupey Hold T2, 2.7-minute @ Las Lomas 1.3-minute @ San Francisco Hold T1, 2-minute @ Sagrado Corazón
Short Turning & Holding II	Short turn T8 & T9 from station 26 to station 6 (Las Lomas) Hold T9, 5.3-minute @ Las Lomas Hold T1, 1-minute @ Sagrado Corazón Hold T2, 2-minute @ Sagrado Corazón
Tren Urbano Solution	Hold T2, 2-minute @ Las Lomas

Table 4-17 J-20: Headway Sequences

1st Trip – Hato Rey (to SC)					
Train #	Do-Nothing	Holding Only	Short Turning I	Short Turning II	TU Scenario
1	4	12	4	4	4
2	4	8	8	4	6
3	24	12	8	8	22
4	2	2	2	2	2
5	2	2	2	2	2
6	2	2	2	2	2
7	2	2	2	2	2
8	2	2	12[24]	8	2
9	2	2	2	8[25]	2
10	2	2	2	2	2
11	2	2	2	2	2
12	2	2	2	4	2
13	2	2	4	4	2

[24] T8 is between T2 and T3 in the short turning I scenario

[25] T8 & T9 are between T2 and T3 in the short turning II scenario

Table 4-17 J-20: Headway Sequences (cont.)

2nd Trip – Complejo (to BC)					
Train #	Do-Nothing	Holding Only	Short Turning I	Short Turning II	TU Scenario
1	4	10	6	5	4
2	4	8	6	5	6
3	22	12	8	8	20
4	2	2	2	2	2
5	2	2	2	2	2
6	2	2	2	2	2
7	2	2	2	2	2
8	2	2	10[26]	5	2
9	2	2	2	7[27]	2
10	2	2	2	2	2
11	2	2	2	4	2
12	2	2	4	4	2
13	4	4	4	4	4
3rd Trip – Hato Rey (to SC)					
Train #	Do-Nothing	Holding Only	Short Turning I	Short Turning II	TU Scenario
1	4	8	6	5	4
2	4	8	6	5	6
3	20	12	8	7	18
4	2	2	2	2	2
5	2	2	2	2	2
6	2	2	2	2	2
7	2	2	2	2	2
8	2	2	8	5	2
9	2	2	2	6	2
10	2	2	2	4	2
11	2	2	4	4	2
12	4	4	4	4	4
13	4	4	4	4	4

[26] T8 is between T2 and T3 in the short turning I scenario

[27] T8 & T9 are between T2 and T3 in the short turning II scenario

Table 4-18 J-20: Analytical Model Results

	Do-nothing	Optimal	Contract	Short-turning I	Short Turning II
Station WT	97133	63962 (34.2%)	87201 (10.2%)	55608 (42.8%)	50850 (47.6%)
Passive Holding	33583	33583	33583	30973	29581
Active Holding	0	3614	385	1738	297
Left Behind WT	3040	1740 (42.8%)	2766 (9.0%)	1936 (36.3%)	2718 (10.6%)
Total WT	133756	102898 (23.1%)	123935 (7.3%)	90254 (32.5%)	83447 (37.6%)
Average WT	5.86	4.51 (23.1%)	5.43 (7.3%)	3.96 (32.5%)	3.66 (37.6%)
# late trains	33	38	33	40	41

Table 4-19 J-20 disruption: Comparison between Optimal Solution (Holding Only and Short Turning I & II) vs. Tren Urbano Solution

Measure	Savings		
	Holding Only	Short-turning I	Short-turning II
Station WT	26.7%	36.2%	41.7%
Active Holding	(838.6%)	(351.5%)	22.8%
Load Left WT	37.1%	30.0%	1.7%
Total WT	17.0%	27.2%	32.7%

Table 4-20 J-20 disruption: Comparison Short Turning (I & II) vs. Holding-only

Measure	Savings	
	Short Turning I	**Short Turning II**
Station WT	13.1%	20.5%
Active Holding	51.9%	91.8%
Left Behind WT	(11.3%)	(56.2%)
Total WT	12.3%	18.9%

The optimal strategies provide significantly better service quality with savings of 23%-38% versus 7% in the Tren Urbano hypothetical case. The same pattern as previously is observed in the station waiting time and the load left waiting time savings. The only component where the optimal solutions do not show significant savings is in the active holding waiting time. For the holding-only scenario, the active holding is almost 10 times the active holding value for the Tren Urbano solution; in the short-turning I scenario, this value is around 4 times the Tren Urbano solution result. However, as mentioned in the previous discussion, the amount of active holding is a small fraction of the total waiting time. The main component, station waiting savings for the optimal solutions significantly greater than either the do-nothing scenario or the Tren Urbano hypothetical solution.

In this case, the passive holding waiting time for the short turning solutions were reduced by 8% and 12% respectively compared with the other strategies. This reduction is caused by the reduction on holding time behind the blockage, given that trains that otherwise would have been held at a station until the blockage was cleared were instead short turned.

Finally, for the Tren Urbano hypothetical solution, the total waiting time savings is reduced by 17%-33% compared with applying the optimal set of control strategies. The service quality is improved significantly by applying the correct set of control strategies. However, the financial impact of providing such an improved service could be as much as $9,000. This financial impact will discourage the contractor from using the optimal control strategies, compared with the hypothetical Tren Urbano solution, in which the financial impact is minimized and there are also some savings in total WT.

4.5 Summary of Results

In general, the use of any reasonable type of control strategies will provide some reduction in total waiting time in the event of a disruption. Obviously, the selection of appropriate control strategies is key in minimizing the negative impacts of the disruption.

The use of holding and short turning in combination will generally result in significant reductions in total waiting time. In the disruptions analyzed short turning produced 9%-20% greater waiting time savings than holding-only. The decision to short turn a train should be based on the location of the disruption and its expected duration. If the disruption occurs early in the alignment, and the short-turning location is before stations with high demand, short turning can be beneficial in minimizing the number of passengers left on the platform in the peak direction of travel. Obviously, it would also depend on the number of passengers travelling in the opposite direction that would be inconvenienced by short turning a train. For long disruptions in particular, short turning helps to reduce headway irregularity, without incurring excessive holding that would significantly increase the amount of active holding waiting time.

The optimal solutions were significantly better at reducing total waiting time than the Tren Urbano hypothetical solution. Some of the negative impacts of these optimal solutions were to increase active holding and the passengers left behind components of the total waiting time compared with the Tren Urbano solution. However, these components are small fractions of the total waiting time; thus the increase in these values does not affect the benefits resulting from minimizing the headway variance along the alignment.

Headway variance minimization is possible by holding trains long enough ahead of the blockage to reduce the preceding headway of the affected train or by introducing trains in front of the blockage (short turning). The earlier the trains are held, the more reduction in station waiting time is achieved. In the disruptions analyzed, the trains were typically held at the first station at which they arrived after the blockage occurred. In the case of Jardines, where trains were held at multiple locations, the holding points were located at stations with high arrival rates (to benefit more passengers from holding), and before arriving at the last six stations.

The other important element in waiting time minimization is the recovery process at the terminals, better known as the dispatching problem. Eberlein (1995) concluded in her thesis that the best station at which to hold trains was the terminal. As mentioned before, she analyzed the case of routine control, where the deviations in headway regularity are mainly caused by heavy demand at stations and small dispatching irregularities. It is less likely to produce bunching if the dispatching headways are well controlled and regular. Later, Song (1998) studied the dispatching problem and developed a heuristic dispatching control model for the MBTA Red Line. The savings obtained ranged up to 14% of passenger waiting time. In the analysis presented here, the dispatching decisions were based on the use of the minimum recovery time. With the two minutes available at the end of each trip to get back on schedule, the objective was to minimize the headway variance between the trains ahead of the blockage and the blocked train (in this case T1, T2 and T3). In addition, if trains ahead of the blockage were not held at earlier stations (because they had already passed heavy boarding stations in the direction towards San Juan at the time of the disruption), we decided to hold them at the terminal in order to minimize the headway variance. The optimal solution obtain here represents a lower bound and it is not necessarily the solution that gives the minimum waiting time, given that only two trains are controlled ahead of the blockage and the short turning was predetermined. However, the results showed that even these optimal control strategies provided significant savings in waiting time with respect to the Tren Urbano hypothetical solution.

The Centro Médico disruption provides the best example of the benefits obtained when dispatching headway variance is minimized. Station waiting time is reduced, not only by reducing the variance through holding but because the headway variance is also minimized each time trains depart from the terminal.

The optimal solutions increase the financial impact of the disruption by delaying trains with holding and skipping stations with short-turning and increasing the number of off-schedule trains. The Tren Urbano hypothetical solution was designed to avoid increasing the number of late trains while controlling them to minimize the disruption impact on waiting time. The hypothetical Tren Urbano control strategies minimize the financial impact of the disruption, but are not the set of control strategies that provide the most benefits. The controller will be inclined to choose the Tren Urbano solution given the minimization of the financial impact, although the service quality is not optimized. Therefore, the financial interest of the contractor is not perfectly aligned with the Authority's and the patrons interest in high service quality.

Chapter 5:

Tren Urbano Control System and Control Strategies

This chapter describes the Automatic Train Regulation (ATR) System developed for Tren Urbano. The ATR system allows the system to maintain either a specific schedule or headway, and corrects any minor deviations by adjusting train speed and dwell times at stations. However, during a non-routine disturbance (i.e. 10 minutes duration or greater) the controller has to make real time decisions about which control strategies should be used to get the system back to normal operation while trying to minimize the impact of the disruption on service quality.

After describing the ATR system, the next step is to analyze how the control system would operate in the event of a major disturbance. The schedule and headway regulation modes will be contrasted in order to determine the best mode of operation during disruptions.

5.1 Tren Urbano Control System

This description of the Tren Urbano control system is divided into three sections: the first section presents an overall description of the capabilities of the control system in terms of operating and control modes for the trains; the second describes dwell time characteristics and speed performance regimes and the way they are modified by the ATR system. The third section describes how the Tren Urbano control system deals with deviations from planned schedule/headway, and how it operates in the event of a disruption.

5.1.1 Control System General Description

Tren Urbano trains are capable of operating fully automatically (currently the operator must close the doors), without the intervention of the operator. The Automated Train Control system (ATC) directs, controls and coordinates all functional operations of each train and consists of three sub-systems: Automatic Train Operation (ATO), Automatic Train Protection (ATP) and Automatic Train Supervision (ATS). ATC operates with information that is transmitted by the wayside control units (WCU) or wayside beacons and processed by the on-board control units (OBCU).

Automatic Train Operation (ATO)

The ATO system "regulates service performance and consists operation, within ATP safety limits, with a high level of efficiency"[28]. ATO is only one of four operating modes:

- Automated Train Operation (ATO)
- Coded Manual Mode (CMM)
- Restricted Manual Mode (RMM)
- By-Pass Mode (BPM)

When ATO is active, the train operator actions are limited to closing the doors, to ordering departure from a station, to checking the tracks for obstacles and to choosing the active cab in the terminal station. The ATP system controls all train movements.

In the CMM operating mode, the train operator controls all train movements (including acceleration and deceleration) and door operations but ATP is still active. This operating mode will be used regularly during off-peak hours to refresh the system

[28] Siemens Transit Team. *Operations and Maintenance Plan: Tren Urbano Project.* Third Edition, October 1999.

operating skills of the operators. If the driver exceeds the speed limit, the ATP system notifies the driver; if the driver does not modify the speed, then the emergency brakes are activated automatically and the train is halted by an emergency brake application.

The RMM is the operating mode in the yard and in the case of ATC system failures. The ATP system limits the train speed to 25 km/h and does not allow motion with doors open; the train operator is completely responsible for driving. The BPM is the operating mode in case of ATP system failure. In this case the operator is completely responsible for all movements of the train and the ATC plays no role.

Automatic Train Protection (ATP)

The second component of the ATC system is the ATP, which "processes vital variants and enforces safe and reliable train operations. The vital oversight system continuously receives information related to on-board and wayside variables, and uses the information to recalculate continuously safe operation parameters"[29]. When ATP is active, emergency brakes are applied if there is any violation of any of the safe operations parameters (i.e. exceeding maximum speed). ATP has three control modes:

- Full Control Mode (FCM)
- Limited Control Mode (LCM)
- Stop Control Mode (SCM)

The FCM is the control mode when the train is in the ATO or CMM operating modes. In this case, the ATP system checks speed restrictions and deceleration, forbids over-running of signaling stopping points, and authorizes door opening at the station platform. The LCM is the control mode in RMM operating mode. In this case the ATP system verifies that the speed is below 25 km/h and that trains do not move with doors open. Finally, the SCM is the ATP control mode during initialization or failure.

[29] Ibid.

Automatic Train Supervision (ATS)

Finally, the third component of the ATC is ATS. This system "allows the Operations Control Center (OCC) to view real time operating conditions of the wayside system and individual consists inclusive of vehicle identification information, train routing, train location, and consist operating status. ATS will automatically respond to manual inputs to control routing, modify dwell times, restrict normal speed regulation, modify schedule adherence technique and order train holds at platforms"[30]. The OCC is where decisions are made in the event of a disruption. The ATS software features include:

- Track Overview: the track overview displays the current state of all track elements at the desired level of detail.
- SCADA System Overview: SCADA is the acronym for Supervisory Control and Data Acquisition. SCADA is a system to monitor, supervise, control and operate all remotely controlled equipment. The wayside control unit (WCU) operates separately from the SCADA system and controls the signal system. This includes interlockings, traffic direction, temporary speed restrictions, and running authorization.
- Interlocking Dialog: the interlocking dialog in the ATS software builds an interface between the OCC and the Mainline and Yards interlockings.
- Train Monitoring and Tracking (TTM): this system provides an internal representation of train movements along the tracks.
- Timetable Editor – this feature allows the controller to download timetables from a database, to activate timetables for the day, to modify the current timetable, and to specify the timetable for the next day. The modifications to the timetable are trip specific. The controller can edit, add, extend, delete, restore, or divert a trip; he is also able to add a train or reverse a train direction. The edit trip feature allows station specific changes to train speeds, arrival/departure and dwell times. The system generates a new timetable when a modification has been made; if there is a conflict, the system notifies the controller of the conflict so that (s)he can make corrections. Whenever a

timetable is modified, the controller has to enter the reason for modification; if no text is entered in the "reason" field, the software does not save the changes.

- Prediction: this feature predicts when each train will arrive at specific station platforms. The system predicts the position of trains 20 minutes in the future and updates these predictions every 30 seconds.
- Automatic Train Regulation: the ATR feature of the OCC includes the ability to specify the type of regulation (either headway or schedule based), to enable or disable the ATR system, and to edit parameters for platforms, trains, sections (from platform to platform), and turnback operations. At the platform level the controller can edit dwell times, make decisions whether or not a train shall skip a station, and whether or not to hold a train at a station platform. Modifications to train parameters include whether or not the trains are ATR regulated, and changes to speed profiles (speed performance regimes are discussed later in this section). The modification is to determine the speed in a track section. Whenever the ATR system is active, it determines dwell times and speeds, with these variables being adjusted according to the ATR regime selected. Input at the software technician's console overrides any ATR function.

5.1.2 Dwell Times and Speed Modifications

The ATR system adjusts train speeds and/or dwell times when a deviation from normal operation occurs based on either schedule adherence or headway adherence. These modifications are the result of the schedule system that operates at the OCC. As mentioned above, the controller inputs in the ATS system the mode of regulation, either headway or schedule based, and whether or not the trains will operate under the ATR system.

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[30] Ibid.

Speed Performance Modifications

There are four speed performance regimes: fast, standard, slow, and rain. The fast and slow performance regimes are (approximately) ±8% deviations from the standard speed respectively, and the rain speed has not yet been fully defined. The standard speed is the speed during normal operation, which permits safe operation within the track geometry and configuration in each block. The fast mode regime represents the highest speed achievable by the vehicles given the civil restrictions in the alignment.

Dwell Time

There are four dwell time assignment modes, which follow a hierarchy where any mode can be overridden by any higher mode. These modes, in decreasing priority, are:

- Vehicle Manual Operation Defaults
- Manual OCC Override
- ATO Adjustments
- Schedule Software Defaults

The Vehicle Manual Operation Defaults correspond to the dwell time when the train is not under ATR operation. This dwell time default value is currently set to 30 seconds. The manual OCC override corresponds to the default values for stations and platforms and is set at the software technician's console. There are three dwell time options in this mode: maximum, minimum, and standard. The current maximum dwell time has a default value of 60 seconds, the minimum default is 15 seconds, and the standard selection has a default value of 30 seconds[31]. The controller is able to set dwell time to any of these three values; however the administrator can also preset these default values. The ATO dwell time adjustment allows for dwell time changes from software defaults by station and platform at the software technician's console. This mode adjusts dwell times in order to keep a train following either the designated schedule or headway. Finally, the schedule software defaults are the dwell times at each station given that a train is following a specific schedule. This is the dwell time that is assigned to each train depending on the schedule assigned at the beginning of service.

5.1.3 Schedule/Headway Regulation Modes

The ATR has two modes of operation: schedule and headway regulation modes and deviations in on-time performance are corrected based on either mode.

If the controller wants to maintain schedule adherence, the system is set to the 'schedule regulation mode'. In this mode performance and dwell times are adjusted if there is a deviation from the schedule. A model will predict if the train is running off schedule and makes the appropriate adjustments until the train gets back to the scheduled arrivals/departures at stations. Adjustments to speed and dwell time occur immediately before the train arrives at a station. When the train is about to arrive at the station, the prediction model estimates the departure time given the normal dwell time (30 seconds). If the train will be off-schedule, the system will estimate how much time the train can recover by adjusting speed. In the case that the train is late, the train will run in fast performance regime; in the opposite situation, the train will operate in slow performance regime. If the speed adjustment does not completely correct the time deviation, then the dwell time would be adjusted. However, if the speed change itself would result in a time adjustment greater than necessary, then the system will only adjust dwell time (at the current station). Dwell time adjustments are bounded by maximum and minimum default values. The speed adjustments are discrete, the fast regime is $1.08*Speed_{normal}$ and the slow regime is $0.92*Speed_{normal}$. There is no intermediate speed between these two speed regimes; a train is traveling at either one of these three specific speeds. If ATR is disabled for a train, then the performance level is set by the ATO.

In addition to adjustment to speed and dwell time for a given train, the system can also make adjustment to the lead train's operation in order to reduce the time between trains. The system keeps track of the lead train's departure time from each station. If the headway exceeds the $H_{scheduled}$ + *default value* (currently set to 8 minutes), then the lead train would be delayed. Although this might seem to be a headway regulation mode, it is a schedule regulation mode because the schedule of each train is based on a fixed

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[31] Siemens Transportation Systems, Inc. *Draft: ATS Users Manual – Tren Urbano*

headway for each time period. Therefore, the ATR system starts adjusting the lead train because there is an increase in its following headway, which means that the trailing train is behind schedule. The type of adjustment depends on whether the delayed train is entering, standing in, or leaving a station. If the delayed train is entering the station, its own speed performance regime is modified as well as its dwell at the station; in addition, the lead train speed and dwell time are modified as it enters the next station. If the train is delayed at the platform, then the lead train speed regime would be adjusted (in this case, it would be set to the slow performance regime), but the lead train dwell time would be unaffected. Finally, if the train were identified as delayed when leaving the station, the lead train would be subject to adjustments to speed performance and dwell time. When the headway falls below $H_{schedule}$ + *default value*, the ATR stops adjusting speed and dwell for the lead train, but keeps adjusting the delayed train performance.

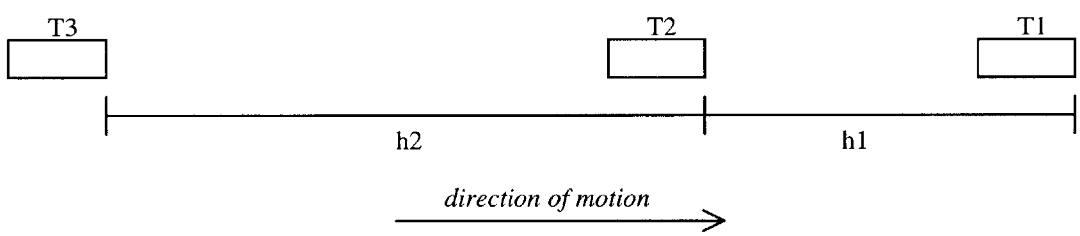
In the headway regulation mode, whenever there is a preceding headway in the system between $H_{scheduled}$ and $XH_{scheduled}$ (a default value) the system will try to increase the speed of the train and/or adjust dwell times, just as in the schedule regulation mode. If H exceeds this value, then the system will also adjust performance of the preceding train until the preceding and following headways are even; then the system would attempt to bring both trains back to the scheduled headway. The lead train adjustments to dwell and speed use the same criteria as the schedule regulation mode.

If trains are operating in manual mode (as opposed to the ATR system regulation mode), the running time between stations will be based on the fast performance regime. In addition, dwell time is fixed at 30 seconds. If the controller manually adjusts dwell times, these can be set only to minimum (15 seconds), standard (30 seconds), or maximum (60 seconds).

In the case of disruptions where the headway exceeds the ATR standards to adjust the lead train performance and dwell, this train is flagged as being on time. This prevents other trains further up the line from being subject to ATR intervention. For example, when a train is delayed to reduce a following gap that is greater than $H_{schedule}$ + *default* *value*, the headway in front of this train is increased. If the lead train were not flagged as being on time, it would also be subject to increase of speed/reduce dwell time to reduce the headway in front of it.

Figure 5-1 presents a hypothetical scenario to clarify the last statement. Assume that h1 = 6 minutes, h2 = 12 minutes, $H_{schedule}$ = 4 minutes, and the control system is operating in the schedule regulation mode. In this case h2 > $H_{schedule}$ + *default value*; therefore, the control system will attempt to delay T2 to reduce h2. However, h1 > $H_{schedule}$, so the control system normally would also attempt to speed up T2; this situation is avoided by flagging the lead train as being on-time, even though it is delayed from its scheduled time.

Figure 5-1 Hypothetical Disruption Diagram



Short turning is dealt with differently in each regulation mode. In the headway regulation mode, the system would always try to maintain the scheduled headway between trains. Therefore, if a train is short turned, the trains in front of and behind this train, in both the former travel direction and its new travel direction, would be controlled so as to maintain the scheduled headway. However, in the schedule regulation mode dealing with short turning is more complicated. A new schedule could be assigned to the short turned train, but this requires a significant amount of time in advance in order to make changes to the current schedule. When the decision to short turn a train is made in real-time (such as during a disruption), the short turned train would keep the current schedule it was assigned, although the train sequence has been altered.

5.2 ATR Modes and Disruption Analysis

From the contractor's point of view, the schedule regulation mode is the best mode of operation to achieve the performance standards specified in the contract. Minor deviations are effectively corrected by the ATR system, and the controller does not need to make control interventions. The schedule is maintained, and the probability of having late trains due to a minor deviation from schedule, such as high demand during the peak hour, is substantially eliminated.

When a major disturbance occurs, however, the use of active control strategies is likely to be helpful to minimize the impact of the disruption on service quality as shown by the examples in Chapter 4. However, the schedule regulation mode does not directly support the use of any control strategy, given that trains are removed from scheduled operation when held, short turned or expressed. For example, if a train is held, when the train departs from the station it will be late; therefore, the ATR will attempt to compensate by changing the speed regime to fast. If the train is still late when it arrives at the next station, the dwell time will be shortened, and so on, until the train is again on schedule. The holding action was intended to reduce the separation between two trains; however, the ATR acts against the control action and tries to return the held train to its original status. The only way to hold a train and maintain the desired effect of this control strategy is by manual control. However, manual control is not recommended given that it introduces stochasticity into the operation as a result of the operators' driving behavior. Manual control is used only at the yards, where the trains are not subject to the ATR system, and during test and refresh periods, where the drivers' capabilities to drive the vehicles are tested and refreshed.

When the ATR delays the lead train to reduce the headway, the train is flagged as being on time to avoid affecting more trains further down the line and to avoid conflicting control actions. However, the train is removed from schedule, and the total adjustments can add up to a value that exceeds the off-schedule threshold at the terminal. Appendix E has the estimated values for an ±8% adjustment to speed. The total time delay for a train by adjusting performance can add up to 1.8 minutes in one direction, not including the time added by adjusting the dwell time. Given that the dwell time can be increased by up to 30 seconds at each platform, 14 platforms x 0.5 min/platform = 7 minutes maximum can be added to running time. A train can be delayed up to 8.8 minutes with only ATR adjustments. Schedule regulation mode is neither minimizing the financial impacts of a disruption since the lead train is being removed from schedule, nor allowing the controller to combine control strategies with the ATR system to reduce the impact of the disruption on service quality.

The headway regulation mode works in a different manner for the same situation. If trains are held or short turned, and the gap between the disrupted train and the lead train is still over the *default value*, the ATR will keep adjusting performance and dwell time to delay the lead train. Once the headways are even, the ATR objective would be to get trains back to their scheduled headway. The controller is able to combine the use of holding with the ATR system, while reducing the headway irregularity more effectively. The benefits would be, first, a reduction in the station WT, given the reduction in headway variance at the stations. Second, a faster recovery of the system from the disruption, given the reductions in running time for each trip that the ATR adjusts. The schedule regulation mode provides for a faster recovery by only adjusting the blocked train and the lead train performance. Although the headways are also subject to reduction in variance, it is not as significant as for the headway regulation mode because these modifications can not be combined with any other strategy.

The selection of the *default value* is also critical for the optimal performance of the ATR system. During minor disturbances, the ATR system is expected to perform efficiently in both the schedule and headway based modes. However, as mentioned above, there are some issues regarding the ATR performance during major disturbances; these issues are related to the manipulation of the lead train. In addition to these issues, the default value is key since it determines when the ATR system starts adjusting the lead train performance. Currently, the *default value* is set to 8-minute for the schedule regulation mode. Assuming the J-10 disruption from Chapter 4, the ATR start making adjustment to T2 (the lead train) 12 minutes after the disruption occurs. T2 is about to reach Río Piedras station when the ATR becomes active for that train, so it has passed 4 stations before the system begins adjusting speed. In the do-nothing scenario analyzed for J-10, overcrowded trains occur at Cupey and Río Piedras stations. The adjustments to the lead train will not benefit the Cupey station because it has passed Cupey before any adjustments are made; therefore, adjusting lead train performance in this case is ineffective in avoiding overcrowding for the disrupted train. The results from Chapter 4 showed that control strategies were more effective if implemented immediately after the disruption. In the optimal scenario, T2 was immediately held at Las Lomas, and this action resulted in no overcrowded trains and significant reduction to passenger waiting time.

The headway regulation mode default value is expressed as $XH_{schedule}$, where X is a percentage of the headway. Currently it is set as 200% of $H_{schedule}$ or $2H_{schedule}$, which means that during the peak period, this value is 8-minute. Using the J-10 do-nothing scenario as an example, the lead train (T2) is about to reach Centro Médico station when the ATR starts adjusting the performance of that train. In this case, the train's performance is adjusted before arriving at Cupey station, helping to improve service quality earlier in the alignment.

The main benefits of the *default value* is when disruptions are expected to be long, given that this is the trigger for adjusting the lead train to minimize the gap between trains. This value should be small enough to allow these adjustments to occur early in the alignment, but not so small that a train running either with its scheduled headway or on schedule is affected by a minor deviation of the trailing train. Using J-10 as an example, it was shown that for a situation where no strategies were applied, an 8-minute *default value* was more effective than 12-minute. A *default value* of 4 minutes for the schedule regulation mode and $2H_{schedule}$ for the headway regulation mode seems to be reasonable during the peak period. However, the *default value* should not be set to a specific value for all time periods. During the off-peak, $2H_{schedule}$ = 24 minutes. Assuming again a disruption at Jardines, the lead train would be at Río Piedras at the moment of the disruption and 12 minutes later would be at Sagrado Corazón station. For such a long headway, it would be better to have a smaller default value, to minimize the impact on waiting time, given that the average waiting time is already high during that period.

The adjustments in the case of non-routine disruptions as described here consider the adjustment to only one train ahead of the trailing train. In the case of the J-10 and J-20 holding-only scenarios, more than one train was held before arriving at the terminal to obtain the maximum benefit from that specific control strategies. This means that there are certain disturbances where the optimal solution consists of controlling more than one train, and this will be a desirable feature in the ATR system. Even assuming that the system had this property, the current contract terms would not support its use, because it would remove more trains from schedule, and would not minimize the financial impact, indeed the financial impact will be increased.

Another concern is the ability to change the timetable at the OCC. Even though the timetable can not be changed unless the modifications are justified and the reason is recorded in the ATS, the Authority does not directly monitor these changes. The contractor may be inclined to adjust the timetable to meet the performance standards. The monthly reports submitted to the Authority should require the contractor to report changes to the timetable and justify these changes. The headway regulation mode avoids this type of situation, because even if there is a modification to the timetable, the scheduled headway is fixed by the time period, and is not a variable that can be changed to meet the standards.

Chapter 6:

Recommendations for Tren Urbano

Chapters 3 through 5 have built the foundation for restructuring the on-time performance terms of the Operations & Maintenance contract. Chapter 3 critically analyzed the structure of the contract terms, and recommended a potential restructuring of these terms based on literature review of reliability and on-time performance measures. Chapter 4 analyzed the use of control strategies during non-routine disturbances on the line and how the contract as currently structured would impact the decisions made by the controller under those circumstances. Finally, Chapter 5 reviewed the Tren Urbano Automatic Train Regulation system and how the two alternative modes of regulation would perform in a disruption scenario in order to determine the best mode of operation.

This chapter integrates the findings of these three chapters and proposes a comprehensive restructuring of the contract terms dealing with on time performance.

6.1 Summary of Results

In chapter 3, the literature review showed that high frequency systems generally use headway adherence as the primary measure for on time performance. The importance of headway consistency is based on the fact that passengers tend to arrive randomly at stations when the service is frequent, because they are not aiming to board a specific train leaving at a specific time.

The Tren Urbano contract terms were created to encourage good service quality; however, there are some key points that should be modified in order to encourage the contractor to provide the best possible service quality. These problem areas are listed below:

- Use of schedule adherence to assess on time performance, instead of headway adherence. Indeed, headway adherence is the recommended basis for assessment given the service frequency of TU.
- The structure of the incentives and penalties is not consistent and is described over most of the relevant region as a step function. If the contractor falls within any of these steps, there is no reason to try to improve performance because he is not rewarded for reducing late trips. A linear function is the best way to structure the incentives and penalties; a simple measure would be to assign a fixed value to each late trip. Another option is to vary the slope between incentives and penalties: a lesser slope for incentives, and a steeper one for penalties. However, the incentive should be generous enough to encourage the contractor to pursue the goal for such incentives, and the penalties should be severe enough to discourage more irregular service over the base level. The recommended measures are discussed in more detail later in this chapter.
- Measure on-time performance only at the terminal station. First, on time performance is important at all stations. If a train was on schedule at 90% of the stations, and a problem occurs just before it arrives at the terminal, it would be penalized even though it met the performance goals during virtually the entire trip. Second, arriving early at a terminal is not a critical fault: passengers are arriving earlier at their final destination, which means that they are not going to miss any connecting services. The main effect would be that the train would have longer recovery time. Including arriving earlier at a terminal to measure on time performance may encourage holding trains

unnecessarily before arriving at the terminal to avoid the penalty, actions that would increase passenger in-vehicle travel time and worsen the level of service.

- Considers each skipped station to be a late trip. For a single trip, if a train skips *n* stations, it means that these are *n* trips counted as late. This penalty is severe, and it might well discourage the contractor from using the best control strategies during a disruption. Skipping stations is one impact of short turning. It is counterproductive to penalize trains being controlled to improve service quality. The results for the non-routine disruptions analyzed in Chapter 4 showed that the combination of holding and short turning frequently provided the most passenger waiting time savings. However, the short turning & holding control strategies resulted in the most severe penalties for all the disruptions analyzed since they produced the highest number of late trips at the terminal. Obviously, the use of short turning has other implications on service quality including the inconvenienced passengers in the original traveling direction of the short turned train. As mentioned in Chapter 2, there are three groups of passenger that are affected by short turning; passengers forced to alight from the train, passengers waiting at stations immediately before the short-turning point, and passengers at stations beyond the short turning point. First, it is very important to make sure that the number of passenger inconvenienced is small compared with the passengers that are benefited. Second, it is important to measure the effect of short turning on passengers. It is important to assess how Tren Urbano users would react in a situation where they are forced to alight from a train, and most important, to make sure passengers in such a situation are given complete and accurate information.
- The incentives and penalties are based on the schedule adherence; however, the schedule is designed based on simulation data and fixed dwell times, which may not accurately represent the real operation. After finishing construction, running times between stations may vary depending on the geometric characteristics and civil constraints resulting from construction.

The pre-revenue tests should be used to determine the final schedule in terms of running time between stations. Dwell times will vary depending on the real demand, and will vary between stations. Having a penalty increasing through the first year of operation is reasonable in the light of these factors; however the current transition to the final penalty structure is too drastic.

An optimization model and an analytical model were used in chapter 4 to assess the impact on passenger waiting time during disruptions of hypothetical control strategies consistent with the contract terms. These results were compared with the set of control strategies and dispatching decisions that minimize passenger waiting time. Disruptions at two locations and of two durations were analyzed. The savings in passenger total waiting time for the optimal set of control strategies ranged from 4%-33% more than the savings from the set of control strategies that minimized the number of late trains as currently defined.

The arguments to support the use of headway as the primary basis of assessing on time performance are as follows:

- The total passenger waiting time savings depend mainly on the station waiting time savings. Since station waiting time depends on headway variance minimization, using headway as a measure for on time performance will result in a better approach to ensure good service quality, even during disruptions. Indeed, the optimal control strategies usually include holding trains at the first station they arrive at after the disruption occurs. Trying to minimize the headway variance as early in the alignment as possible minimizes total passenger waiting time, which translates into improved service quality during a disruption.
- Station waiting time is simply the sum of on-platform waiting time at all stations, which supports the use of measuring on-time performance at all stations. As mentioned above, optimal control strategies generally include holding the lead train at the first station at which it arrives immediately after the disruption occurs. That action minimizes the number of stations severely

impacted by the disruption, in addition to minimizing the station waiting time. If on time performance is measured at all stations, the contractor will try to reduce the impact of the disruption by applying control strategies immediately when the disruption occurs to minimize the number of stations with high headway variance, and consequently minimizing the financial impact of the disruption. For a trip arriving at the terminal, the on-platform waiting time at that station is zero. The terminal waiting time is a function of when the trip departs from that station. Therefore, the terminal station should not be used to measure waiting time-related on time performance for trips that are arriving at the terminal; however, it should be included to measure on-time performance for departing trips.

- The station waiting time reductions are affected by the dispatching decisions at the terminal. The two-minute minimum recovery time available at the terminal was used in the optimal solution to minimize the headway variance. In contrast, the recovery times in the Tren Urbano hypothetical solution were used to get the trains affected by the disruption back on schedule.

Chapter 5 analyzed the ATR modes of operation to determine the best measure of on time performance based on which mode provides the best service quality. Since the ATR system modes are either schedule regulation or headway regulation, selecting one mode or the other should logically be tied to the way on time performance is measured. Currently, the contractor is expecting to use the schedule mode to ensure the system keeps operating as scheduled, given the contract definition of on time performance.

From the analysis of both regulation modes, the headway regulation mode resulted in the best mode of maintaining good service quality during a disruption. It allows the controller to use control strategies that otherwise would not be effectively used because the schedule regulation mode does not effectively support them. In fact, the ATR schedule regulation mode acts against the intent of the control strategies. Since the headway regulation mode attempts to maintain headway regularity, and headway regularity is a measure of service quality from the user's perspective (given that it minimizes passenger waiting time), the recommendation is to use headway adherence as the basis of measuring for on time performance.

6.2 Final Recommendations for Contract Terms Restructuring

The points above provide a basis for proposing a restructuring of the contract terms. This section will present the recommended revised structure for the contract terms with respect to on time performance.

6.2.1 On time Performance

Base on time performance on headway adherence, and measure headways at all stations. A proposed definition for off-schedule trips is given below:

1. A trip is defined as off-schedule if the departing headway at any station is greater than $H_{schedule}$ + 2 minutes. The base performance level is set at 98.5% of the trips on time during a month, or the equivalent of 4 late trips per day.
2. Measure the percent of trains that complete their trips within 2 minutes of scheduled trip time, and set a performance level of 98.5% of trips with travel time less than $TT_{schedule}$ + 2 minutes.
3. The first trip of the day must be judged on time based on schedule adherence, because that train is following the schedule, and there is no train ahead of it to define headway adherence. Therefore, the standard will be set to define that particular trip on time if it arrives within ± 2 minutes of the scheduled arrival.

It is proposed that the final structure of contract terms read: "A trip is defined as off-schedule if either (a) the headway at any station is greater than $H_{schedule}$ + 2 minute, or (b) the travel time is greater then $TT_{schedule}$ + 2 minute". The only exception is the first trip of the day, which is defined as off schedule if it arrives at any station more than ± 2 minutes from the scheduled arrival time. The performance level is that 98.5% of all trips should be on time. On-time performance is measured at all points along the alignment because data is already collected by the system and reflects passenger boarding the system at every station.

6.2.2 Exceptions to Performance Enforcement

Although the provision for exceptions is recommended, they should be carefully defined. A first option is to be more specific in the definition of exceptions. For example, the Authority should specify under which conditions incidents caused by a Patron are indirectly the responsibility of the Contractor. Assume that there is a threat caused by a user at a station which affects the movement of trains; probably the cause of this incident was a lack of security at the station, which is the contractor's responsibility. Also, in the case of a medical emergency, the Authority may grant the exception if the emergency is resolved in less than X minutes. That provision is reasonable if the contractor is expected to provide first aid service and to have certain equipment and trained personnel to deal with this type of incident. If the contractor relies on other entities to deal with this kind of situation, then the exception should be granted without being subject to certain restrictions.

A second option to restructuring the exceptions is to reduce them to simplify the enforcement of the contract provisions. For example, the exceptions to the contract provisions could be restricted to Force Majeure and any problem caused by an Authority action. Also, it is important to define whether or not other trips indirectly affected by any exception should be considered as an excused trip or not. If these trips are not excused, the performance allowance could be increased (currently set as 1.5%), to take them into account. This second option is recommended given that it is easier to implement and will reduce disputes about classifying specific problems as exceptions.

Another recommendation to the current exception definition is to exclude the excused trips when estimating the incentives, similar to the penalty estimation. The current definition includes exceptions to estimate incentives, which might be viewed as indirectly penalizing the contractor, given that the incentive is reduced.

6.2.3 Incentive/Penalty Structure

There are several options that could be used as alternatives to the current structure, which are derived from the current incentive/penalty values. Indeed, the incentive ($/late trip) corresponding to more than (Base-50) late trips and the penalty ($/late trip) corresponding to more than (Base+50) late trips are not changed for options 1 and 2, and the incentive is not changed for option 3.

1. Use a linear relation defined by the equation:

$$Incentive\,/\,Penalty = \$750 * (Base\ Number - \#\, late\ trips) \qquad (6\text{-}1)$$

where a positive value is an incentive, and a negative value is a penalty. This is the simplest way to structure the incentives and penalties for on time performance, given that an additional trip represents a constant marginal financial impact of $750 dollars regardless the number of off-schedule trips. Figure 3-5 in Chapter 3 is a graphical representation of this option.

2. Have variable cost penalties (incentives) depending on the number of off-schedule trips. The base number represents $0 incentive/penalty. If the number of late trips is below the base, the incentive increases as the number of late trips decreases from $500 per late-trip avoided until it reaches a maximum value of $750 per late-trip avoided. Conversely, for late trips over the base number, the penalty increases as the number of late trips increases, from $500 per late-trip initially until it reaches the maximum value of $750 per late-trip. Figure 6-1 is a graphical representation of this incentive/penalty structure; and Table 6-1 presents the functions for each range of values. The ranges correspond to the current ranges in the contract terms. To set the penalty/incentive marginal cost of an additional trip the penalty (or the incentive) currently set to estimate the value of each trip was used. For example, if the base number is 124 late trips, in the current contract, from 1-10 trips over the base the penalty is $5,000, and is constant within that range. Given that the range has 10 trips,

it can be changed to \$5,000/10 = \$500/trip. The next range goes from 11 to 20 trips over the base, and the penalty is \$11,000; therefore, \$11,000/20 = \$550/trip. This calculation is repeated for all ranges and for the incentive structure. The pattern shows that every 10 trips (over the base number) the penalty increases \$50, until it reaches \$750/trip. In the case of the incentive structure, it decreases \$50 every 10 trips, until it reaches \$500/trip, which is the minimum incentive.

This option could also be combined with option 1, where the incentives can be described by a linear function (Equation 6-1) and the penalties are variable, increasing the marginal cost as the number of late trips increases.

Figure 6-1 On-time Performance (Option 2)

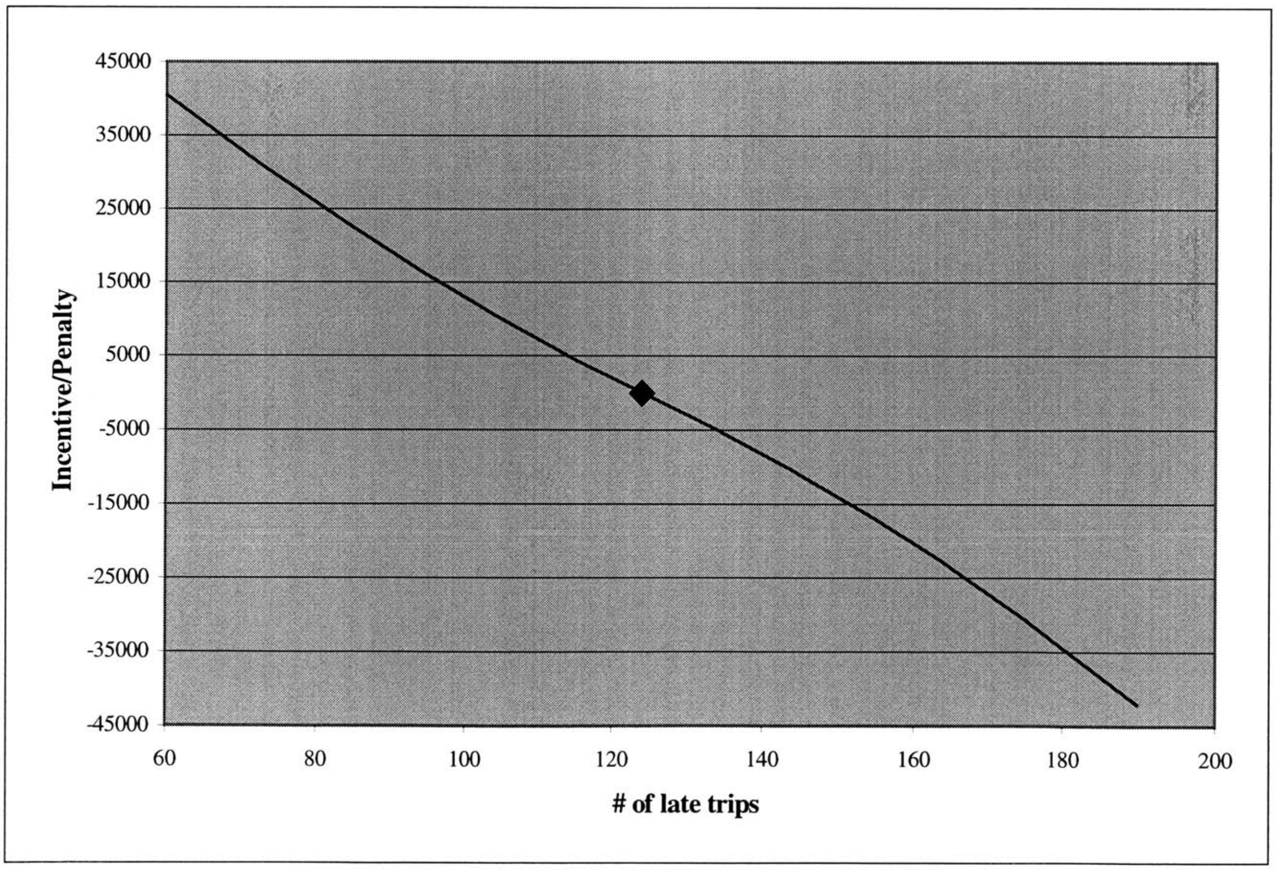


Table 6-1 On-time performance – Incentive/Penalty Structure (Option 2)

# of Off-Schedule Trips Per Month		Incentive/Penalty Structure	
General	Example (Base = 124)	Incentive	Penalty
Less than (Base-50)	Less than 74	\$30,000 + \$750 x (74 – #late trips)	
(Base-50) – (Base-41)	74-83	\$23,000 + \$700 x (84 – #late trips)	
(Base-40) – (Base-31)	84-93	\$16,500 + \$650 x (94 – #late trips)	
(Base-30) – (Base-21)	94-103	\$10,500 + \$600 x (104 – #late trips)	
(Base-20) – (Base-11)	104-113	\$5,000 + \$550 x (114 – #late trips)	
(Base-10) – (Base-1)	114-123	\$500 x (Base – #late trips)	
Base Number	124	No incentive	No penalty
(Base+1) – (Base+10)	125-134		\$500 x (Base – #late trips)
(Base+11) – (Base+20)	135-144		\$5,000 + \$550 x (#late trips – 134)
(Base+21) – (Base+30)	145-154		\$10,500 + \$600 x (#late trips – 144)
(Base+31) – (Base+40)	155-164		\$16,500 + \$650 x (#late trips – 154)
(Base+41) – (Base+50)	165-174		\$23,000 + \$700 x (#late trips – 164)
More than (Base+50)	More than 175		\$30,000 + \$750 x (#late trips – 174)

3. Use a structure similar to the incentive/penalty structure for the missed trips shown in Chapter 3, Figure 3-3. Here, penalties are more severe than the incentives. To achieve this effect in the on time performance structure, the penalties can be set as *n* times the base incentive. For example, assuming a linear function for incentives and penalties, the equations that can be used to describe this alternative are as follows:

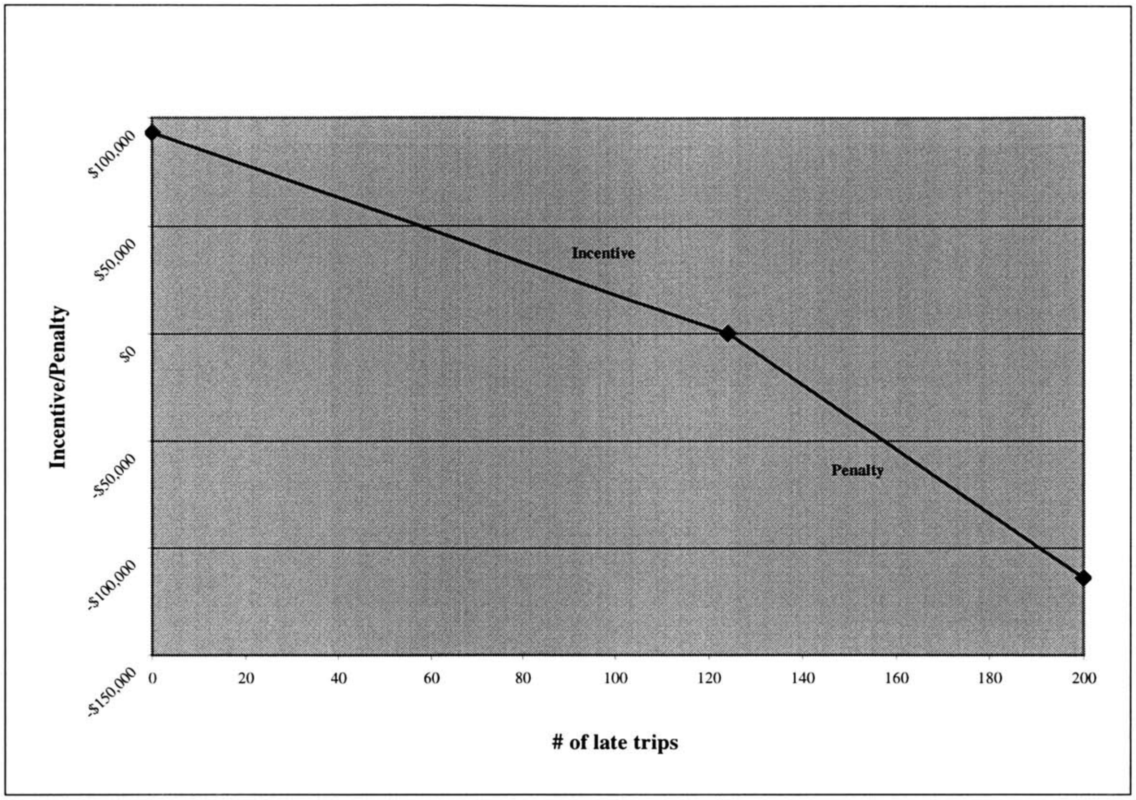
$$Incentives = \$750 * (Base\ number - \#late\ trips) \tag{6-2}$$

and

$$Penalties = n * \$750 * (Base\ number - \#late\ trips) \tag{6-3}$$

Figure 6-2 shows an example of the structure proposed, assuming $n = 2$.

Figure 6-2 Incentive/Penalty Structure - On Time Performance (Option 3, n=2)



4. Another possible modification to the incentive/penalty structure for on time performance is the variation of incentive/penalty during the first year of operation. In Chapter 3, Figure 3-2 shows a drastic transition from the first year of revenue service to subsequent years. During the first year the increase is constant and then it increases drastically to the final incentive/penalty for the rest of the contract period. The increase from the first day of operation to the first year of revenue service should be similar to the missed trips incentive/penalty structure transition from day 1 to the first year of revenue operation. The increase is constant until it reaches the final incentive/penalty structure that will be used during the contracting period.

Since the incentive/penalty structure for on time performance is divided into five periods, the final incentive/penalty structure was divided into five. Using option 1 as an example, the cost of a late trip is $750/late-trip. Divided by five this value is reduced to $150/late-trip. Therefore, the following set of equation can describe the line for each of the five periods:

Month 1-3:

$$Incentive\,/\,Penalty = \$150 * (Base\ Number - \#\,late\ trips) \tag{6-4}$$

Month 4-6:

$$Incentive\,/\,Penalty = \$300 * (Base\ Number - \#\,late\ trips) \tag{6-5}$$

Month 7-9:

$$Incentive\,/\,Penalty = \$450 * (Base\ Number - \#\,late\ trips) \tag{6-6}$$

Month 10-12:

$$Incentive\,/\,Penalty = \$600 * (Base\ Number - \#\,late\ trips) \tag{6-7}$$

Year 1+:

$$Incentive\,/\,Penalty = \$750 * (Base\ Number - \#\,late\ trips) \tag{6-8}$$

This same structure can also be used for options 2 and 3; evidently, the variation to the equations presented here for option 1 is on how the cost of a late trip is defined over a range of values. Finally, these incentives and penalty should be in effect after schedule adjustments to real operation. The pre-revenue operation is key for the adjustments to running time between stations given the final geometric and civil characteristics of the alignment.

The final recommendation for the incentive/penalty structure is to use the combination of options 1 & 2 (proposed in the discussion of option 2) to determine the incentives and penalties, based on the fact that every ten late-trips increases the penalty structure is more severe. Even though the incentive/penalty amounts are derived from the original structure, it appears to be more restrictive than the original, and might encourage an increased effort to achieve the on time performance standards. In addition, the transition between periods should follow the recommendations from point 4 above.

6.2.4 Skipped Stations Definition

As mentioned in Chapters 3 and 4, skipping station strategies are used occasionally during disturbances to improve service quality at certain locations in the alignment where demand is considerably high. The current contract penalizes each skipped station as a late trip, which is a severe penalty. The aim of these restrictions should be to avoid the excessive use of station skipping if trips do not achieve the on time performance criteria as currently defined. Since late trips are defined at the terminal, the contractor might be encourage to skip stations to save time and get back to the schedule. The new definition for on time performance as proposed in section 6.2.1 does not lead to this type of behavior given that on time performance is measured at each station. To assure the use of station skipping strategies only during serious disturbances, we can add an additional condition to the off schedule trip definition to allow station skipping only when an incident of more than 10 minutes duration occurs. This exception will require the Authority to request reports on station skipping, including justification for such action. However, this exception ensures that if the best solution during an incident requires either expressing, or short turning or deadheading, the contractor will not be thinking of minimizing the number of late trip, but looking for the best combination of control strategies to improve service.

6.2.5 Missed Trips Clause

The missed trips clause as well as the incentive/penalty structure are reasonable in terms of current practice and measurement. There are no recommended changes for this performance standard.

Chapter 7:

Summary and Future Research

Tren Urbano is the first rapid transit system to be privately contracted in North America. Incentives and penalties are included in the O&M contract to ensure good service quality. These particular characteristics make Tren Urbano a showcase worldwide, and its success will not only affect the use of this new transit mode in Puerto Rico, but also the potential use of private contracted services for other rapid transit systems in the US or elsewhere.

This thesis focused on the Tren Urbano Operation & Maintenance contract terms for on time performance, how its current structure might affect service quality during a disruption, and recommends a new structure that is aimed at meeting the contractor, the Authority and the users' interests. This is the first research attempt to explore the impacts on service quality of including incentive and penalties in Operations and Maintenance contracts for transit systems. This chapter summarizes the findings and the recommendations for contract terms restructuring. In addition, future research is recommended.

7.1 Summary and Conclusions

This research was divided into four major tasks: (1) analysis of contract terms structure based on transit theory and practice, (2) analysis of disruption scenarios comparing optimal strategies versus TU hypothetical strategies, (3) analysis of ATR system modes and how they operate during a major disturbance, and (4) recommended contract terms structure based on the results of the three previous stages of the research. These four tasks are summarized below, presenting the major findings and conclusions for each of them.

7.1.1 Tren Urbano Operations Performance Analysis

The Tren Urbano on time performance clause measures the number of late trains at the terminal. In theory, passengers are more interested in headway regularity than in schedule adherence when they are using a high frequency service. Their arrivals are not timed to board a specific vehicle, but to board the next arriving vehicle. This means that passenger arrivals are random; therefore, their waiting time is affected by the headway variance, if constant arrival rate is assumed within a short period of time.

If good service quality is defined by the minimization of passenger waiting time, then headway regularity should be used to define on time performance and service reliability. The first recommendation is to use headways as the measure for on time performance and develop the incentive/penalty based on the deviation from the $H_{schedule}$.

Another deficiency found in the current structure of the on time performance clause is measuring on time performance only at the terminal. First, early arrival at the terminal is penalized; if the system were based on schedule adherence, measuring early arrival at a terminal is irrelevant because it does not affect any passenger boarding, since there are no boardings (inbound) at the terminal. Early arrival in schedule-based systems is important, because passengers time their arrival to minimize their wait for the next vehicle. If a vehicle arrives early, some passengers will be affected, because they will have to wait for the next vehicle. Therefore, early arrival is important in low frequency system, with headways greater than 10 minutes, which is not the case of Tren Urbano during the base and peak periods. Nonetheless, on time performance is important at all stations, and measuring deviations from $H_{schedule}$ should be considered at all stations. Failure to meet on time performance at any station should be considered a late trip.

According to the current contract term for on time performance if a train maintains the $H_{schedule}$ or the schedule (as on time performance is currently stated in the contract) at all stations, but then before arriving the terminal suffers a disruption, the trip is penalized, although it meets the performance standards at all stations but the terminal.

Skipped stations are included in the definition of a late trip. Moreover, a trip that skips *n* stations is considered as *n* late trips. This penalty is severe and may discourage the use of control strategies that include station skipping strategies during disruptions, which could be favorable for such situation.

The structure of the incentive/penalty also presented some inconsistencies in the way trips were rewarded or penalized. First, the marginal cost of a late trip could range from zero to $9,000. The incentives and penalties were described by a step function in a region around the base number of allowed late trips. If the number of late trips were within any of these steps then the contractor is not encouraged to improve performance, because an improvement neither increases the incentive nor decreases the penalty. The best way to define the incentives and penalties is to assign a value to each saved/additional late trip. This value can vary between incentives and penalties, where a late trip over the base is valued higher than a late trip below the base.

The missed trip clause and the incentive/penalty structure are properly designed to define missed trips. There was no recommendation to change the current structure; indeed, the incentive/penalty structure is the base for recommending the new on time performance structure.

The exceptions included in the contract are too generous and are not clearly defined. The recommendation was to reduce the number of exceptions and modify the way incentives were estimated in the case of late trip exclusions. The current structure indirectly penalizes the contractor for the exceptions when estimating the incentives for a given month.

7.1.2 Control Strategies and Disruption Analysis

During a disruption, the controller has to take control decisions in order to minimize the impact of a disruption on service quality. The strategies used are holding, short turning and expressing. Previous research has shown that holding is the most effective strategy to minimize passenger waiting time and that the highest benefits of controlling trains are obtained when combining holding and short turning.

To analyze the impact of a disruption two methods were used: an optimization model (Shen, 2000), and an analytical model. The first was used to determine the set of control strategies that minimized passenger waiting time; the latter was used to estimate the total passenger WT including the impact of dispatching decisions at the terminal.

Two possible strategies were explored: the optimal solution, and the hypothetical Tren Urbano solution. The optimal solution consisted of the set of control strategies obtained from the model developed by Shen (2000). The analysis included holding-only and the combination of holding with short turning. The hypothetical Tren Urbano solution consisted of adding a constraint to Shen's model that represented the contract terms for on time performance. This strategy only includes holding; short turning is not used because the contractor incurs a substantial penalty whether a short turned trip is considered late or missed. Expressing was not considered in the analysis for two reasons. First, because the contractor would never be encouraged to use it, given that if n stations are skipped n late trips result. Second, its contribution to minimizing passenger waiting time is modest, and not as significant as short turning and holding.

The disruptions were analyzed at two different locations (Jardines and Centro Médico) and two different lengths of time (10 and 20 minutes). Jardines is the third station in the direction towards San Juan; Centro Médico is the tenth station in the same direction. The time period analyzed was the AM peak, when the highest demand during the weekday operation is forecast.

In general, the use of any type of control strategies, even the minimum effort, provides reductions in total waiting time. Obviously, the decision which control strategies to use to minimize the impact of a disruption is key to obtaining the greatest benefits. Basically the purpose of using Shen's model was to obtain these optimal strategies that will minimize the impact of the disruption during the disruption and after it is cleared.

The use of holding combined with short turning result in significant reductions to total waiting time. The short turning based strategies result in 7%-19% greater savings compared with the holding-only strategies in the disruption situations analyzed. The decision to short turn a train should be based in the location of the disruption and its expected duration. If the disruption occurs early in the alignment, and the short-turning location is before stations with high demand, short turning can minimize the number of passengers left on the platform in the peak direction of travel. Obviously, it would also depend on the number of passengers that might be inconvenienced in the opposite direction. For long disruptions, short turning helps to reduce headway irregularity, without incurring excessive holding that would increase significantly the amount of active holding waiting time.

The optimal solutions were significantly better at reducing the total waiting time than the Tren Urbano hypothetical solution. Some of the negative impacts of these optimal solutions were to increase active holding waiting time and the passenger left waiting time compared with the Tren Urbano solution. However, these components are a small fraction of the total waiting time; thus the increase of these values does not affect the benefits already resulting from minimizing the headway variance along the alignment.

Headway variance minimization is possible by holding trains long enough to reduce the preceding headway of the disrupted train, or by introducing trains in front of the blockage (short turning). The earlier the trains are held, the greater the reduction to station waiting time. In the disruptions analyzed, the trains were generally held at the first station they arrived at after the disruption. In the case of Jardines, where trains were held at multiple locations, the holding points were located at station with high arrival rates (to benefit more passengers from holding), and before arriving at the last six stations in the San Juan direction.

The other important component to minimizing waiting time is the recovery decisions at the terminals. In the analysis presented here, the dispatching decisions were based on the use of the minimum recovery time. With the two minutes available at the end for each trip to get back to schedule, the objective was to minimize the variance between the trains ahead of the blockage and the disrupted train. Also, in the case that trains ahead of the blockage were not held immediately after the disruption, trains were held at the terminal to reduce the headway variance, and consequently, the passenger waiting time.

The Centro Médico disruption provides the best example of the benefits obtained when dispatching headway variance is minimized. Station waiting time is reduced, not only by reducing the variance through holding but because the headway variance is also minimized each time trains depart the terminal.

The optimal solutions increased the financial impact of the disruption by delaying trains with holding and skipping stations with short-turning and increasing the number of off-schedule trips. The Tren Urbano hypothetical solution was designed to avoid the increase of late trips while controlling them to minimize the disruption impact on passengers. The Tren Urbano hypothetical solution minimizes the impact of the disruption, but it is not the optimal set of control strategies to provide the best service quality. The controller is inclined to choose the Tren Urbano hypothetical solution given the minimization of the financial impact, although the service quality is not optimized. The results obtained with this analysis demonstrate that headway regularity is the best approach to providing the best service quality during a disruption by minimizing the passenger waiting time.

7.1.3 Tren Urbano ATR System Analysis

The ATR system for Tren Urbano has two modes of operation: schedule regulation mode and headway regulation mode. The purpose of these systems are to maintain either the schedule or the headway by adjusting speed and dwell times when there are disturbances that affect the system.

The headway regulation mode is the most efficient mode of operation, since it is the only mode that allows the controller to use control strategies to improve service quality during a disruption. The schedule regulation mode does not support the use of control strategies, and even after the controller has dictated a control strategy, the ATR system acts against the desired effects of the control strategy.

7.1.4 Contract Terms Restructuring

The previous three tasks are the foundation to build the proposed new on time performance contract terms. It is evident from the results obtained with the three tasks that the headway adherence is the best measure for on time performance.

The recommendations, discussed in detail in Chapter 6, are as follows:

1. Base on time performance on headway adherence by defining a late trip as one that has a headway greater than $H_{schedule}$ + 2 minutes at any station and/or a trip with a travel time greater than $TT_{schedule}$ + 2 minutes. If a trip fails to comply with this standard at any station, that trip is considered late. The first trip is off-schedule based on schedule adherence at any station.
2. Modify the incentive/penalty structure by assigning a value in $ per late-trip for trips below the base (incentive region) and trips above the base (penalty region). The value assigned to a late trip can vary in order to make penalties more restrictive than the incentives.
3. Modify the transition between incentives and penalties from the first day of operation to the first year of operation. The incentives and penalties are too low

during the first year and then increase abruptly to the final incentive/penalty structure. The proposed transition is to increase the incentive and penalties steadily until they reach the maximum incentive/penalty that will be enforced during the rest of the contract. The transition is similar to the current transition for the missed trips contract term.

4. Allow station skipping during disruptions longer than 10 minutes to avoid discouraging the controller from using expressing, deadheading and/or short turning.
5. The exceptions to the contract term provisions should be carefully revised and redefined because currently they are too generous. The recommendation is to include as exceptions only events caused by Force Majeure or Authority actions. Also define the estimation of incentives similar to the estimation of penalties when exceptions are considered.
6. The current structure for the missed trips contract term seems reasonable in terms of current practice and measurement. Also the incentive/penalty structure is rational; moreover, it was used as an example to define the on time performance incentive/penalty structure.

7.2 Future Research

Tren Urbano is still under construction, with operations expected to begin in about two years. Issues related to operations and maintenance are important for the success of Tren Urbano as a new mode of transportation for the San Juan Metropolitan Area. This section suggests areas of future research not only for Tren Urbano, but also for application to any rail system.

7.2.1 Control System Quantitative Disruption Analysis

The analysis of the control system presented here is qualitative. The conclusions raised in this thesis were based on understanding the way the system operates; however, there is no quantitative analysis of the savings from using the headway regulation mode versus the schedule regulation mode. In addition, it would be useful to study how the ATR system is combined with the control strategies during a disruption and how the quality of service will be impacted.

For this type of analysis, a simulation model of the control system would be necessary, given that including the characteristic of the control system in the optimization model presented here would too complex, if not impossible.

7.2.2 Passengers Behavior

The analysis presented in this thesis does not take into consideration how the passengers react to the different control strategies. In the case of holding, we reduced the in-vehicle delay time due to holding by half, because previous research (Abdel-Aty, Kitamura and Jovanis, 1995) showed that in-vehicle time is less onerous than on-platform waiting time and that 0.5 was a reasonable weight. However, we have not included how passengers may react to being "dumped" from a short turned or expressed train. It is reasonable to consider a weight higher than 1.0 because these passengers are inconvenienced by being forced to alight from one train and wait for the next train. Both weights for on-board delay and on-platform waiting time could be estimated by determining the reaction of Tren Urbano users to both situations.

7.2.3 Guidelines for Control Decisions during Non-routine Disturbances

A research area that has not been fully analyzed in the field of urban transportation is the development of guidelines that the controller could use during a disruption. Control strategies have been studied and some optimization and heuristic models have been developed to deal with disruption scenarios (routine and non-routine disturbances) in real time or to improve dispatching decisions. However, all of them require programming effort and integration with the current operations system, given the real time data requirements from these models. This represents additional costs that the agency either may not be able afford or is unwilling to spend given other needs they might be facing.

During disruptions, the controller makes decisions based on experience but also can be assisted by a set of guidelines to help the controller to make good decisions under the pressure of a serious incident. This research showed that any attempt to reduce the headway variance during a disruption has a positive impact on passenger waiting time. Nevertheless, the decisions made based on the controller's judgement might not be close to the optimal solution which minimizes the impact of the disruption.

For Tren Urbano, the importance of having guidelines to deal with a disruption is critical, because currently there is no local expertise available for rail system operations. The contract requires having a detailed methodology for abnormal and emergency operation (clause 1.4, O&M Contract). However, in the case of Tren Urbano, a general set of guidelines developed for any rail system might not be completely effective, because of the current constraint in operations control that is imposed by the contract terms, as well as the ATR system modes characteristics. Guidelines and contingency plans for Tren Urbano should be developed considering the control system and the actual structure of the contract terms.

The guidelines should be designed to recommend appropriate scenarios for holding, short turning and expressing during different time periods depending on the expected arrival rates, passenger loads, the location and duration of the disruption, and system characteristics.

The framework to develop these guidelines is divided into three steps:

1. Prepare a database with incident classification and expected duration. This database will help the controller to make more accurate estimates of incident duration, which is important to determine the magnitude of the control strategies to be applied.

2. Study control strategies and identify how to use them effectively depending on the disruption duration and demand characteristics.
3. Combine steps 1 & 2 and apply the recommendation from each of these to a specific system. The result is a table (or computer software) that will recommend the best set of control strategies depending on the disruption location and duration (see Figure 7-1).

Figure 7-1 Guidelines Structure Example

Time Period: AM Peak

Frequency: ________________

Location	**Duration**	**Holding**		**Short Turning**		**Expressing**		**Deadheading**	
		Stations	H. time (max.)	Last Station	# trains	Segment	# trains	Segment	# trains
Stations 1-3	5-10 min								
	10-15 min								
	15-20 min								
	20+ min								
Station 3-6									

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Appendix A:

Optimization Model (Shen, 2000)

In this Appendix, we introduce the variables, objective function and constraints from Shen's model. For a detailed description of the model formulation, assumptions, constraints and variables refer to Shen (2000).

The model was used in this thesis to determine the optimal set of control strategies that would minimize passenger WT, considering both on-platform and on-board waiting time. A constraint was added in order to assess the optimal set of control strategies for TU, based on the current contract terms structure.

A.1 Variables Definition and Notation

The following is a list with the definitions of the variables used in the model.

$a_{i,t}$ = Arrival time of train *i* at terminal *t*

$ah_{i,k}$ = Arrival headway for train *i* at station *k*

$al_{i,k}$ = The number of alighting passengers for train *i* at station *k*

$b_{i,k}$ = The number of boarding passengers for train *i* at station *k*

$d_{i,k}$ = Departure time for train *i* at station *k*

$dh_{i,k}$ = Departure headway for train *i* at station *k*

$dp_{i,k}$ = Departure time for the train preceding *i* at station *k*

$dw_{i,k}$ = Dwell time of train *i* at station *k*

dw_k^0 = The typical dwell time at station *k* in that time period

$h_{i,k}$ = Maximum platform waiting time for train *i* at station *k*

$ht_{i,k}$ = Holding time of train *i* at station *k*

i_{BL} = Blocked or disabled train

$l_{i,k}$ = Passenger load on train *i* departing station *k*

$l_{i,k}^{0}$	=	Approximate passenger load on train *i* departing station *k*
$late_{i,t}$	=	1 if arrival time of train *I* is later than the departure of its predecessor at terminal *t*, 0 otherwise
$p_{i,k}$	=	The number of passengers left behind by train *i* at station *k*
$p_{i,k}^{P}$	=	The number of passengers left behind by predecessor of train *i* at station *k*
$so_{i,m}$	=	1 if train *i* operates on segment *m*, 0 otherwise
$st_{i,m}$	=	1 if train *i* is short turned on the crossover track of segment *m*, 0 otherwise
$t_{k,k'}^{s}$	=	Short-turning time from station *k* to *k'*
t_{BL}	=	Earliest time at which the blocked train or disabled train can move
t_{mc}	=	Minimum recovery time at terminal
$y_{j,i,m}$	=	1 if train *j* precedes train *i* on segment *m*, 0 otherwise
$z_{i,k}$	=	Variable to approximate the quadratic term of platform waiting time for train *i* at station *k*
$zt_{i,k}$	=	Variable to approximate the quadratic term of holding time for train *i* at station *k*
A_k	=	Passenger arrival rate at station *k*
H_k	=	Minimum non-inter-station-stopping headway at station *k*
L	=	Train Capacity
M	=	Sufficient large number
Q_k	=	Passenger alighting fraction at station *k*
R_k	=	Non-inter-station-stopping running time from station (*k-1*) to station *k*
S	=	The set of stations in the impact set
$Sch_{i,t}$	=	Schedule dispatching time of train *i* at station *k*
S^{t}	=	The set of terminal stations in the impact set
G	=	The set of segments in the impact set
T	=	The set of trains in the impact set
$T_{i,m}^{P}$	=	The set of trains that can be predecessor of train *i* on segment *m*
$T_{i,m}^{s}$	=	The set of trains that can be successor of train *i* on segment *m*
U^{iw}	=	Weight for in-vehicle waiting time

A.2 Model Formulation

The objective of this model is to minimize the impact of a disruption. The two components, as mentioned above, to measure service quality will be the on-platform waiting time and delay on-board as expressed in the following equation:

$$Min \quad \sum_{i\in T}\sum_{m\in G} so_{i,m} \sum_{k\in m}\{\frac{A_k}{2} * h_{i,k}^2 + p_{i,k}(d_{i+1,k} - d_{i,k}) + U^{iw}[\frac{A_k}{2} ht_{i,k}^2 + (l_{i,k} - A_k ht_{i,k}) ht_{i,k}]\}$$

(A-1)

Subject to:

$$d_{i,k} - d_{i,k-1} - R_k - dw_{i,k} \geq M(so_{i,m} - 1), \quad \forall\, i\in T, k\in m, m\in G \tag{A-2}$$

$$d_{i,k} - dp_{i,k+1} - H_{k+1} + R_{k+1} \geq M(so_{i,m} - 1), \quad \forall \quad i\in T, k\in m, m\in G \tag{A-3}$$

$$dp_{i,k} - d_{j,k} \geq M(y_{j,i,m} - 1) \tag{A-4}$$

$$dp_{i,k} - d_{j,k} \leq M(1 - y_{j,i,m}), \quad \forall \quad i\in T, j\in T_{i,m}^{p}, k\in m \tag{A-5}$$

$$ht_{i,k} - d_{i,k} + d_{i,k-1} + R_k + dw_{i,k} \geq M(so_{i,m} - 1), \quad \forall \quad i\in T, k\in m, k\in S', m\in G \tag{A-6}$$

$$h_{i,k} \geq d_{i,k} - dp_{i,k} - ht_{i,k}a + M(so_{i,m} - 1), \quad \forall \quad i\in T, k\in m, k\notin S', m\in G \tag{A-7}$$

$$a_{i,t} - d_{i,t-1} - R_t \geq M(so_{i,m} - 1), \quad \forall \quad i\in T, t\in S', t\in m \tag{A-8}$$

$$d_{i,t} - a_{i,t} - t_{cm} \geq M(so_{i,m} - 1), \quad \forall \quad i\in T, t\in S', t\in m \tag{A-9}$$

$$d_{i,t} - Sch_{i,t} \geq M(so_{i,m} - 1), \quad \forall \quad i\in T, t\in S', t\in m \tag{A-10}$$

$$a_{i,t} - dp_{i,t} - M * late_{i,t} \leq 0, \quad \forall \quad i\in T, t\in S' \tag{A-11}$$

$$ht_{i,t} - [(d_{i,t} - a_{i,t})late_{i,t} + (d_{i,t} - dp_{i,t})(1 - late_{i,t})]so_{i,m} = 0, \quad \forall \quad i \in T, t \in S^t, t \in m \quad \text{(A-12)}$$

$$h_{i,t} - [(a_{i,t} - dp_{i,t})late_{i,t}]so_{i,m} = 0, \quad \forall \quad i \in T, t \in S^t, t \in m \quad \text{(A-13)}$$

$$d_{i,k'} - d_{i,k} - t^s_{k,k'} - dw_{i,k'} \geq M(st_{i,m} - 1), \quad \forall \quad i \in T, k \in m, m \in G, \textit{a crossover track exists at the end of } m$$

(A-14)

$$ht_{i,k'} - d_{i,k'} + d_{i,k} + t^s_{k,k'} + dw_{i,k'} \geq M(st_{i,m} - 1), \quad \forall \quad i \in T, k \in m, m \in G, \textit{a crossover track exists at the end of } m$$

(A-15)

$$l_{i,k} - A_k(d_{i,k} - dp_{i,k}) - (1 - Q_k)l_{i,k-1} - p^p_{i,k} + p_{i,k} = 0 \quad \forall i \in T, k, k-1 \in S \quad \text{(A-16)}$$

$$l_{i,k} \leq L_{\max} \quad \text{(A-17)}$$

$$p^p_{i,k} - p_{j,k} \geq M(y_{j,i,m} - 1), \quad \forall i \in T, j \in T^p_{i,m}, k \in m \quad \text{(A-18)}$$

$$p^p_{i,k} - p_{j,k} \geq M(1 - y_{j,i,m}), \quad \forall i \in T, j \in T^p_{i,m}, k \in m \quad \text{(A-19)}$$

$$p_{i,k} - (p^p_{i,k} + A_k h_{i,k} + l_{i,k-1}(1 - Q_k))st_{i,m} \geq 0, \quad \forall i \in T, k \in m, (k+1) \in (m+1), m \in G, \textit{a crossover track exist at the end of } m.$$

(A-20)

$$st_{i,m} - so_{i,m} \leq 0, \quad \forall i \in T, m \in G, \textit{a crossover track exist at the end of } m. \quad \text{(A-21)}$$

$$so_{i,m+1} + st_{i,m} \leq 1, \quad \forall i \in T, m \in G, \textit{a crossover track exists at the end of } m. \quad \text{(A-22)}$$

$$so_{i,m} - so_{i,m-1} \leq 0, \quad \forall\, i \in T, m \in G, \text{ the margin between } m \text{ and } (m-1) \text{ is not a crossover track.}$$

(A-23)

$$y_{i,i+1,m} + st_{i,m} + st_{i+1,m} \geq 1, \quad \forall \quad i \in T, m \in G, \text{the end of } m \text{ is a crossover track} \tag{A-24}$$

$$y_{i,j,m'} - st_{i,m} \leq 0, \quad \forall \quad i \in T^{p}_{j,m}, m \in G, \text{the end of } m \text{ is a crossover track} \tag{A-25}$$

$$\sum_{m \in G} st_{i,m} \leq 1, \quad \forall \quad i \in T \tag{A-26}$$

$$\sum_{j \in T^{p}_{i,m}} y_{j,i,m} = 1, \quad \forall \quad i \in T, m \in G \tag{A-27}$$

$$\sum_{j \in T^{s}_{i,m}} y_{i,j,m} = 1, \quad \forall \quad i \in T, m \in G \tag{A-28}$$

$$y_{i,j,m} + y_{j,i,m} \leq 1, \quad \forall \quad i \in T^{p}_{j,m}, j \in T^{p}_{i,m}, m \in G \tag{A-29}$$

$$y_{j,i,m} - so_{i,m} \leq 0, \quad \forall \quad j \in T^{p}_{i,m}, m \in G \tag{A-30}$$

$$d_{i_{BL},k_{BL}} \leq t_{BL} \tag{A-31}$$

$$y_{i,j,m},\ st_{i,m},\ so_{i,m} \in \{0,1\} \quad \forall\, i \in T, k \in S, m \in G \tag{A-32}$$

$$d_{i,k},\ dp_{i,k},\ dw_{i,k},\ h_{i,k},\ p_{i,k},\ p^{p}_{i,k},\ l_{i,k} \quad \geq 0, \quad \forall\ i \in T, k \in S, m \in G \tag{A-33}$$

The first two terms in the objective function are related to the on-platform waiting time. The first of these estimates the on-platform waiting time for the passengers that arrive to the station from the departure of the preceding train until the end of dwell of train i. The second term estimates the waiting time of passenger left by the preceding train. The final term in this equation estimates the on board delay.

In order to be able to use a lineal solver, the objective function should be simplified. After simplification of non-separable terms and quadratic functions, the objective function is:

$$Min \sum_{i\in T}\sum_{m\in G} so_{i,m} \sum_{k\in m} \{\frac{A_k}{2} * z_{i,k} + p_{i,k}(H_k + dw_k^0) + U^{iw}[\frac{A_k}{2} zt_{i,k} + l_k^0 ht_{i,k}]\} \quad \text{(A-34)}$$

Subject to (in addition to the constraints above):

$z_{i,k} \geq a_n * h_{i,k} + b_n,$ *for* $n = 1, 2, \ldots, i \in T, k \in m, m \in G$ (A-35)

$zt_{i,k} \geq a'_n * ht_{i,k} + b'_n,$ *for* $n = 1, 2, \ldots, i \in T, k \in m, m \in G$ (A-36)

Appendix B:

Ridership Data for Tren Urbano (2010 Forecast)

Table B-1 Estimated Boardings, Alightings, Loads, Arrival Rates and Alighting Fractions for TU AM Peak hour – To San Juan

Station Name	To San Juan				
	Boardings (per train)	Alightings (per train)	Normal Load	Arrival Rate (pass/min)	Alighting Fraction
Bayamón	229	0	229	57.2	0.0000
Deportivo	94	0	322	23.4	0.0003
Río Bayamón	20	4	339	5.1	0.0120
Torrimar	18	3	354	4.5	0.0096
Martínez Nadal	15	11	358	3.8	0.0317
Las Lomas	28	8	378	7.0	0.0220
San Francisco	26	7	398	6.6	0.0173
Centro Médico	31	29	400	7.8	0.0728
Cupey	69	46	423	17.2	0.1147
Río Piedras	68	50	441	17.1	0.1172
Universidad	21	123	340	5.2	0.2776
Piñero	27	25	342	6.8	0.0730
Domenech	5	23	323	1.2	0.0684
Roosevelt	2	85	241	0.6	0.2614
Hato Rey	2	84	159	0.5	0.3466
Sagrado Corazón	0	160	0	0.0	1.0000

Table B-2 Estimated Boardings, Alightings, Loads, Arrival Rates and Alighting Fractions for TU AM Peak hour – To Bayamón

Station Name	To Bayamón				
	Boardings (per train)	Alightings (per train)	Normal Load	Arrival Rate (pass/min)	Alighting Fraction
Sagrado Corazón	72	0	72	18.1	0.0000
Hato Rey	17	0	89	4.3	0.0000
Roosevelt	18	1	106	4.5	0.0149
Domenech	10	3	113	2.6	0.0321
Piñero	8	5	116	2.1	0.0437
Universidad	39	29	127	9.8	0.2467
Río Piedras	65	15	177	16.2	0.1188
Cupey	28	26	178	6.9	0.1491
Centro Médico	9	22	165	2.3	0.1228
San Francisco	4	23	147	1.1	0.1367
Las Lomas	6	11	142	1.5	0.0780
Martínez Nadal	7	5	143	1.7	0.0349
Torrimar	3	11	135	0.8	0.0772
Río Bayamón	5	8	133	1.4	0.0591
Deportivo	0	55	78	0.1	0.4170
Bayamón	0	78	0	0.0	1.0000

Appendix C:

Tren Urbano Running Times, Distances and Speed between Stations

Table C-1 Running Times, Distances, Dwell and Speed between Stations

Station	Running Time (MATRA)			Dwell Time	Arrival	Departure	Distance between stations		Speed	
	Sim 7/98	Sim 1/98	Average				Station (EOP)	Distance	(km/hr)	(mi/hr)
Bayamón							10198.0			
Deportivo	94.6	93.0	93.8	30	93.8	123.8	11151.0	953.0	36.6	22.7
Río Bayamón	143.2	159.6	151.4	30	275.2	305.2	13591.6	2440.6	58.0	36.0
Torrimar	63.5	64.7	64.1	30	369.3	399.3	14541.9	950.3	53.4	33.1
Martínez Nadal	96.6	102.8	99.7	30	499.0	529.0	16332.0	1790.1	64.6	40.1
Las Lomas	64.0	63.3	63.7	30	592.7	622.7	17222.5	890.5	50.4	31.3
San Francisco	76.4	77.1	76.8	30	699.4	729.4	18384.8	1162.3	54.5	33.9
Centro Medico	84.6	84.8	84.7	30	814.1	844.1	19421.1	1036.3	44.1	27.4
Cupey	93.2	94.2	93.7	30	937.8	967.8	20731.1	1310.0	50.3	31.3
Rio Piedras	97.7	108.2	103.0	30	1070.8	1100.8	22128.0	1396.9	48.9	30.3
Universidad	59.6	57.7	58.7	30	1159.4	1189.4	22772.0	644.0	39.5	24.5
Piñero	79.4	79.4	79.4	30	1268.8	1298.8	23605.2	833.2	37.8	23.5
Domenech	63.9	63.2	63.6	30	1362.4	1392.4	24274.0	668.8	37.9	23.5
Roosevelt	72.4	71.8	72.1	30	1464.5	1494.5	25112.5	838.5	41.9	26.0
Hato Rey	56.6	58.9	57.8	30	1552.2	1582.2	25789.9	677.4	42.2	26.2
Sag. Corazón	78.1	74.0	76.1	240	1658.3	1898.3	26651.7	861.8	40.8	25.3
Hato Rey	90.4	86.1	88.3	30	1986.5	2016.5	25651.9	861.8	35.2	21.8
Roosevelt	61.1	61.1	61.1	30	2077.6	2107.6	25016.5	635.4	37.4	23.3
Domenech	79.4	79.0	79.2	30	2186.8	2216.8	24136.0	880.5	40.0	24.9
Piñero	65.4	65.3	65.4	30	2282.2	2312.2	23467.2	668.8	36.9	22.9
Universidad	77.1	78.8	78.0	30	2390.1	2420.1	22634.0	833.2	38.5	23.9
Rio Piedras	56.1	55.9	56.0	30	2476.1	2506.1	21990.0	644.0	41.4	25.7
Cupey	94.2	102.1	98.2	30	2604.3	2634.3	20592.9	1397.1	51.2	31.8
Centro Medico	96.3	98.9	97.6	30	2731.9	2761.9	19283.1	1309.7	48.3	30.0
San Francisco	84.3	83.6	84.0	30	2845.8	2875.8	18246.8	1036.3	44.4	27.6
Las Lomas	72.1	70.2	71.2	30	2947.0	2977.0	17084.5	1162.3	58.8	36.5
Martínez Nadal	63.6	63.0	63.3	30	3040.3	3070.3	16194.0	890.5	50.6	31.4
Torrimar	98.6	97.4	98.0	30	3168.3	3198.3	14403.9	1790.1	65.8	40.8
Río Bayamón	70.6	69.2	69.9	30	3268.2	3298.2	13453.6	950.3	48.9	30.4
Deportivo	143.2	159.5	151.4	30	3449.5	3479.5	11013.0	2440.6	58.1	36.0
Bayamón	86.0	85.2	85.6	240	3565.1	3805.1	10060.0	953.0	40.1	24.9

Appendix D:

Crossover Tracks Information

Table D-1 Crossover Tracks Locations and Distance from Platforms

Between Stations	Location	Distance from Platform (to San Juan) - meters	Distance from Platform (to Bayamón) - meters
Bayamón & Deportivo	Sta 104+04.14 @ Sta 104+65.87	206.13	547.13
Deportivo & Río Bayamón	Sta 130+34.02 @ Sta 130+86.92	1883.02	366.68
Torrimar & Martínez Nadal	Sta 152+57.11 @ Sta 153+18.82	715.21	875.18
Martínez Nadal & Las Lomas	Sta 165+54.84 @ Sta 166+66.62	222.84	414.88
San Francisco & Centro Médico	Sta 190+47.10 @ Sta 191+00.00	662.3	183.10
Cupey & Río Piedras	Sta 215+13.60 @ Sta 215+66.50	782.5	423.50
Piñero & Domenech	Sta 236+38.71 @ Sta 236+91.61	33.51	444.39
Hato Rey & Sagrado Corazón	Sta 261+80.00 @ Sta 262+41.72	390.1	271.98

Appendix E:

Performance Adjustment Data

Table E-1 Speed Performance Adjustment Data

Station	Speed		Speed Change (km/hr)		Running Time		Time (seconds)		Time (minutes)	
	(km/hr)	(mi/hr)	8%	-8%	Fast	Slow	Reduction (Fast)	Increase (Slow)	Reduction (Fast)	Increase (Slow)
Bayamón										
Deportivo	36.6	22.7	39.5	33.7	86.8	101.9	7.0	8.1	0.12	0.14
Río Bayamón	58.0	36.0	62.7	53.4	140.2	164.6	11.2	13.2	0.19	0.22
Torrimar	53.4	33.1	57.6	49.1	59.4	69.7	4.7	5.6	0.08	0.09
Martínez Nadal	64.6	40.1	69.8	59.5	92.3	108.4	7.4	8.7	0.12	0.14
Las Lomas	50.4	31.3	54.4	46.3	58.9	69.2	4.7	5.5	0.08	0.09
San Francisco	54.5	33.9	58.9	50.2	71.1	83.4	5.7	6.7	0.09	0.11
Centro Medico	44.1	27.4	47.6	40.5	78.4	92.1	6.3	7.4	0.10	0.12
Cupey	50.3	31.3	54.4	46.3	86.8	101.8	6.9	8.1	0.12	0.14
Rio Piedras	48.9	30.3	52.8	44.9	95.3	111.9	7.6	8.9	0.13	0.15
Universidad	39.5	24.5	42.7	36.4	54.3	63.7	4.3	5.1	0.07	0.08
Piñero	37.8	23.5	40.8	34.8	73.5	86.3	5.9	6.9	0.10	0.11
Domenech	37.9	23.5	40.9	34.9	58.8	69.1	4.7	5.5	0.08	0.09
Roosevelt	41.9	26.0	45.2	38.5	66.8	78.4	5.3	6.3	0.09	0.10
Hato Rey	42.2	26.2	45.6	38.9	53.5	62.8	4.3	5.0	0.07	0.08
Sag. Corazón	40.8	25.3	44.1	37.5	70.4	82.7	5.6	6.6	0.09	0.11
Hato Rey	35.2	21.8	38.0	32.3	81.7	95.9	6.5	7.7	0.11	0.13
Roosevelt	37.4	23.3	40.4	34.4	56.6	66.4	4.5	5.3	0.08	0.09
Domenech	40.0	24.9	43.2	36.8	73.3	86.1	5.9	6.9	0.10	0.11
Piñero	36.9	22.9	39.8	33.9	60.5	71.0	4.8	5.7	0.08	0.09
Universidad	38.5	23.9	41.6	35.4	72.2	84.7	5.8	6.8	0.10	0.11
Rio Piedras	41.4	25.7	44.7	38.1	51.9	60.9	4.1	4.9	0.07	0.08
Cupey	51.2	31.8	55.3	47.1	90.9	106.7	7.3	8.5	0.12	0.14
Centro Médico	48.3	30.0	52.2	44.4	90.4	106.1	7.2	8.5	0.12	0.14
San Francisco	44.4	27.6	48.0	40.9	77.7	91.3	6.2	7.3	0.10	0.12
Las Lomas	58.8	36.5	63.5	54.1	65.9	77.3	5.3	6.2	0.09	0.10
Martínez Nadal	50.6	31.4	54.7	46.6	58.6	68.8	4.7	5.5	0.08	0.09
Torrimar	65.8	40.8	71.0	60.5	90.7	106.5	7.3	8.5	0.12	0.14
Río Bayamón	48.9	30.4	52.9	45.0	64.7	76.0	5.2	6.1	0.09	0.10
Deportivo	58.1	36.0	62.7	53.4	140.1	164.5	11.2	13.2	0.19	0.22
Bayamón	40.1	24.9	43.3	36.9	79.3	93.0	6.3	7.4	0.11	0.12