Evaluation of Bus Priority Strategies for BRT Operations

by

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Abstract

Bus Rapid Transit (BRT) uses strategies such as exclusive bus lanes, off-vehicle fare collection, high quality vehicles and stations, signal priority, among others. Transit Signal Priority (TSP) is frequently seen as an option to improve performance of public transportation systems at the operational level. TSP is an operational strategy that aims at reducing the delays at intersections for transit vehicles. The goal is to reduce travel times and improve service reliability. The use of transit priority strategies, properly designed for BRT, can complement its other features and potentially contribute to improved performance. However, BRT corridors present a number of challenges and operating characteristics that differ from conventional corridors which are worth considering.

This thesis evaluates the potential of incorporating different priority strategies, especially TSP, into BRT operations both in the U.S. and in developing countries. A corridor from Boston, MA and a corridor from Santiago, Chile are analyzed, assessing TSP strategies that consider different conditions such as headway, loads, and traffic demand in a BRT context. Results for both case studies support the belief that TSP can provide travel time reductions for transit vehicles, together with reductions in headway variability. However, results proved to be very sensitive to increases in traffic congestion and transit frequency. The research provides insights into the potential of TSP under medium and high levels of traffic demand, as well as under higher frequencies. Further research is necessary to make the models more robust and test the sensitivity of the parameters of the priority strategies. Evaluation of other priority strategies like the use of full exclusive bus lanes and signal coordination are also included.

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Chapter 1

Introduction

Severe road congestion and population growth in metropolitan areas constrains urban mobility. New infrastructure investments are not always feasible or effective. Therefore, a reasonable option is to improve public transportation systems to make them more attractive to the general public, in order to increase the transit mode share.

Bus Rapid Transit (BRT) has received a lot of attention in the last several years, and the benefits of its implementation are starting to be noticed. BRT is defined by the Transit Cooperative Research Program (TCRP) as a "rubber-tired rapid-transit mode that combines stations, vehicles, services, running ways, and Intelligent Transportation System (ITS) elements into an integrated system with a strong positive identity that evokes a unique image"(Levinson et al. 2003).

BRT systems have shown to be effective in significantly increasing ridership and improving operations while proving to be cost-effective. Hinebaugh (2009) states that passenger surveys have revealed that these increases in ridership, which have been occurring in most of the corridors where BRT has been implemented, have come from new users that did not use public transit before. These increases in ridership, as well as increases in transit-oriented land developments, demonstrate that BRT could be an effective alternative for addressing the current mobility issues metropolitan areas are facing.

The objective of this research is to focus on operational aspects of BRTs, specifically on assessing some of the bus priority strategies like signal priority and the use of exclusive bus lanes that are part of the key features that characterize these systems.

1.1 Bus Rapid Transit

Bus Rapid Transit is one of many approaches adopted to improve the performance of bus service. BRT is a high-quality bus service that implements several features in an attempt to mimic the performance level of a rail system but at a lower cost and with the easier implementation of a bus system.

BRT originated in Curitiba, Brazil, in 1972, with an idea brought up by the city's then mayor, and later governor, architect Jamie Lerner. The mayor's objective was to come up with a new approach to accommodate population growth and to limit severe congestion that had been witnessed in many cities. His main idea revolved around implementing a sort of subway system, but running next to traffic, while using buses instead of trains (EMBARQ, 2009). Lerner's idea proved to be a successful approach to deal with congestion and sprawl, given his policy of development around those BRT corridors. Soon after, many cities around the world like Bogota, Colombia; Mexico City, Mexico; and Quito, Ecuador decided to implement it as well.

BRT made its way into the U.S. during the late 1970s starting in Pittsburg with the implementation of an initial BRT segment in 1977 followed by a second segment in 1983 (Miller and Buckley, 2000). Today, these two corridors serve approximately 120,000 passengers daily and, combined with light rail projects, have generated an effective transit-oriented environment in Allegheny County. The initial experiences in Pittsburg were followed in 1980 with the implementation of a BRT corridor in Seattle. The BRT corridor used a high-occupancy (HOV) lane, which included a segment in a downtown tunnel used by more than 40% of vehicles with destinations in the downtown area. In Texas, the cities of Houston and Dallas later implemented express bus services on freeway HOV lanes as well, and both cities have plans to expand their systems, which would lead to over 100 miles of BRT service. In 1997 Miami, Florida also initiated an 8.2-mile BRT route with exclusive bus lanes to provide transfers to the city's heavy rail system.

The characteristics that have made BRT systems so effective and popular are the advanced features used, which are usually not present on conventional bus systems, plus the fact that they can be implemented quickly and incrementally, without the need for a high level of investment. These features include a combination of dedicated running ways, off-vehicle fare collection, all-door boarding, signal priority, high-quality stations and vehicles, and unique branding.

Different BRT systems have implemented different forms of running ways, which vary based on the level of interaction with traffic and the physical location of the lane. These range from mixed-traffic lanes, to curb bus lanes that allow right-turning vehicles, to completely segregated bus-ways. While some conventional buses are still being used by several BRT systems, articulated diesel buses are commonly used for BRT operations (Levinson et al. 2003). Many of the new vehicles that are being used have lower platforms and more than three doors for easier boarding and alighting. New designs for bus stations are also being used, with different amenities to provide passengers with more comfort and security, as well as off-vehicle fare collection systems to speed up the boarding process and reduce dwell times.

Bus Rapid Transit systems are designed to address the specific needs of the areas they serve, and can be implemented in incremental ways. BRTs typically have whole day frequent services, with midday headways of 15 minutes or less and peak headways of 10 minutes or less. More than 80% of BRT systems around the world have at least some type of exclusive bus lane, approximately 66% have stations in addition to bus stops, and 17% have off-vehicle fare collection (Levinson et al. 2003). Only three systems have all the advanced features, which are Curitiba's median bus-ways, Bogota's Transmilenio, and Quito's Trolebus.

Many research studies have been performed to evaluate the conditions under which these systems would be successful. Smith (1967) argues that BRTs are more suitable "in cities where downtown must attract its visitors from a wide, diffused area." He explains that BRTs adapt more easily than rail systems to changes in land use and to the population they serve. The author explained that BRTs should be seen as the alternative for providing high-capacity service in cities that do not have rail systems, or that have rail systems that have low coverage or operate at over-capacity service.

Hidalgo and Gutierrez (2013) indicate that there are currently more than 120 cities with BRTs or High Level of Service buses (BHLS), with more than 280 corridors providing service to about 28 million passengers a day. According to the authors, 99 of these cities (16 in the developing world) have just recently implemented BRT corridors in the last 12 years, mainly due to the impressive success of the first BRT systems in Curitiba, Bogota, and Mexico City. However, the authors state that despite the growing deployments of advanced bus service systems, many systems are currently suffering from problems due to poor planning, implementation, and/or operation. They argue that there is a big need to address these issues to keep an image and maintain these systems as competitive alternatives to rail systems. They point out that BRT is still in its "infancy" and there is a need for further research and analysis.

This study focuses on evaluating bus priority strategies for BRT operations using two case studies, one in Boston, MA, and another in Santiago, Chile. The city of Boston adopted BRT because of the city's urgent need to provide more transit capacity and better access to major activity centers. The Silver Line along the Washington Street corridor is used in this study in particular because of its recent TSP implementations along four major signalized intersections, which did not seem to be working at its full potential. A corridor in Santiago was also selected because of the city's need to improve the performance of their bus systems given the dramatic decline in bus ridership, and to shift passengers from the subway system, which is running over capacity. Carmen Avenue in Santiago was selected because of its current problems with service reliability on routes 204 and 204 express, even after the implementation of a bus-and-taxi only lane. The city of Santiago has an urgent need to improve the travel conditions of its bus corridors to be able to complement the subway while avoiding the high investment needs required for a rail-based system. The Carmen Avenue corridor is one of the many services that run parallel to the metro and provide an alternate path for the home-to-work commute.

The study of these two corridors intends to provide different perspectives in the analysis, such as different levels of transit demand and different operating characteristics. A corridor like the Silver Line in Boston could be used to appropriately represent typical characteristics found in the U.S., while a corridor like Carmen in Santiago will give a perspective of something more typically experienced in South America, where the majority of the population is captive to the public transportation systems, and therefore the systems have services with higher frequencies and service demand.

1.2 Transit Priority

Increases in congestion and transportation costs have highlighted the need to investigate new transit priority strategies to develop more transit-oriented environments with greater system efficiencies. Some priority strategies that have demonstrated potential for improving transit efficiency are the implementation of exclusive bus lanes and of Intelligent Transportation System (ITS) technologies.

However, it has been shown that the support for these implementations depends on the level of traffic demand on the roads where they will be employed (Todd, 2006).

Exclusive bus lanes provide a good alternative for transit vehicles that are subject to traffic congestion, improving the performance and appearance of bus transit. Yet, dedicated bus lanes reduce the available capacity for general traffic, and therefore are usually justified only for transit systems that are operating with high frequencies and have considerable passenger demand, like BRTs.

Another option that is frequently used by BRTs or BHLS is Transit Signal Priority (TSP). In general, TSP corresponds to an operational strategy that speeds up the movement of transit vehicles through intersections controlled by traffic signals. It is often viewed as a solution for addressing operational challenges faced by public transportation systems. Examples of such operational challenges are bus delays caused by vehicle interactions and by traffic signals, which also lead to higher headway variability. Transit signal priority strategies are separated into two types: passive and active. Passive priority strategies are those in which fixed transit-weighted signal settings are applied, while active priority strategies are those where dynamic detection is used and signal settings are changed in real time to speed up the transit vehicles.

Applications of transit priority strategies within BRT systems are similar to those applied to conventional bus systems, as the underlying concept is the same. However, BRT corridors present a number of challenges and unique operating characteristics that are worth considering. Such challenges include higher frequency of service, higher levels of demand, exclusive lanes, etc. The work to date on the different priority strategies has focused mainly on conventional bus systems, while experiences with BRT corridors are still limited.

Implementing transit priority strategies is a challenging task. The feasibility of applying them to existing conditions without critically affecting traffic is often a major concern. Although strategies like the implementation of bus lanes and passive signal priority can be tested in the field without significant investment, this is not the case for active priority strategies. Although a lot of field tests have taken place, it is generally not feasible due to the high costs that are typically incurred.

Microscopic traffic simulation is a feasible method to evaluate transit priority strategies such as signal priority, signal coordination, and exclusive bus lanes under a variety of operational conditions. Simulation is a particularly useful approach to model complex traffic interactions and evaluate the potential benefits for transit vehicles under a variety of "what if" scenarios.

1.3 Objectives

The objective of this research is to investigate and evaluate bus priority strategies that could benefit BRT systems and could be incorporated into their operations, both in the U.S. and in developing countries. Transit signal priority strategies were evaluated on two corridors: one in Boston, Massachusetts and another in Santiago, Chile. Current conditions of the corridors were simulated, and several conditional strategies were tested in terms of headway and bus loads. Projections of current conditions were also analyzed to determine how TSP can best be implemented in BRT corridors with different characteristics in terms of demand levels, frequency of service, etc.

An evaluation of the effects of conditional TSP is performed, and recommendations for implementation are provided. The potential of signal coordination and implementation of bus lanes are also discussed as possible strategies to improve BRT operations.

1.4 Thesis Outline

The remainder of this thesis is organized as follows. Chapter 2 gives an overview of transit priority concepts and reviews the literature and experience of TSP with conventional bus systems and BRTs and discusses the main lessons learned. Chapter 3 details the methodology and the data needed and discusses the experimental design. Chapter 4 details the specifics of the Boston corridor as well as the analysis of results. Chapter 5 describes the Santiago case study in detail, together with the analysis of results. Chapter 6 presents the research conclusions and recommendations, including further research directions.

Chapter 2

Background and Literature Review

Transit priority strategies can be divided into two categories: infrastructure design or traffic control. This chapter presents the latest implementations of priority strategies for buses, especially in Bus Rapid Transit (BRT) systems and High Level of Service buses (BHLS), and the experience from the literature review.

2.1 Transit Priority

Transit priority strategies that are based on infrastructure design typically include the implementation of exclusive bus lanes, as well as specific street designs to help enable faster loading process, and also reduce conflicting interactions between transit vehicles entering and exiting the stops. Other more innovative strategies like Bus Lanes with Intermittent Priority (BLIP) implement lanes that can be used by general traffic as they would normally, but with the instruction to leave the lane and yield right-of-way when a bus approaches (Todd, 2006).

Transit priority strategies based on traffic control measures can be applied to specific intersections or the whole network. These measures include using fixed-time signal settings that favor transit vehicles, or providing signal priority where the location and/or load of transit vehicles can be monitored in real time (Skabardonis, 2000).

2.2 Signal Priority

Transit Signal Priority is an operational strategy intended to improve transit travel time efficiency as well as to improve schedule or headway adherence by facilitating the movement of transit vehicles through signal-controlled intersections. This section provides information on signal control in general and signal priority strategies in particular.

2.2.1 Traffic Signal Control

Traffic control systems are used to provide favorable signal timings to motorists to avoid conflicts at intersections and enhance traffic throughput. This is accomplished by signal timing plans that control the movements in an intersection, allocating time between the different approaches, plus coordination among intersections. This section provides some background on traffic signal control systems and introduces the different concepts and terminology (ITE, 2009).

In traffic signal control systems, right-of-way is assigned to a combination of non-conflicting movements for a portion of a signal timing cycle. This portion of time is called a phase. There are typically three intervals in a phase: green, yellow, and all-red. A controller will go from one interval to the other before switching to the next phase to complete the cycle. Figure 2-1 shows an example of the different movements allowed in an intersection, while Figure 2-2 shows the different phase splits that are organized in a loop (or ring) and separated by conflicting movement groups.

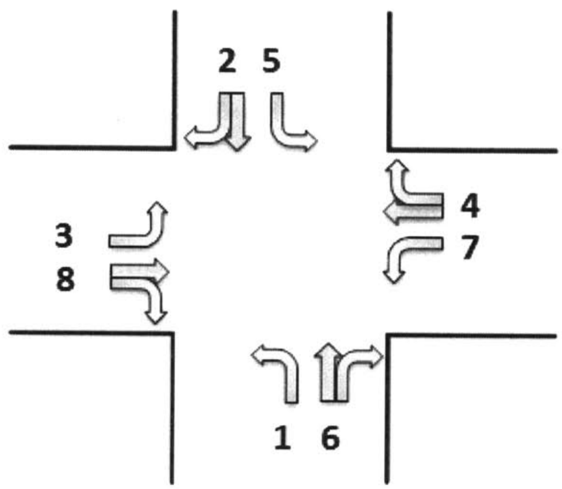


Figure 2-1: Example of vehicular movement in an intersection

This example shows a four-approach intersection with eight possible movements. Note that some movements have been categorized as couples because they are composed of a protected movement, or a movement that has allowed right-of-way, and a permissive movement, or a movement that requires drivers to yield to possible conflicting movements. For example, movement 6 consists of a protected north movement and right turn movement which allow drivers to turn right (Gordon and Tighe, 2005).

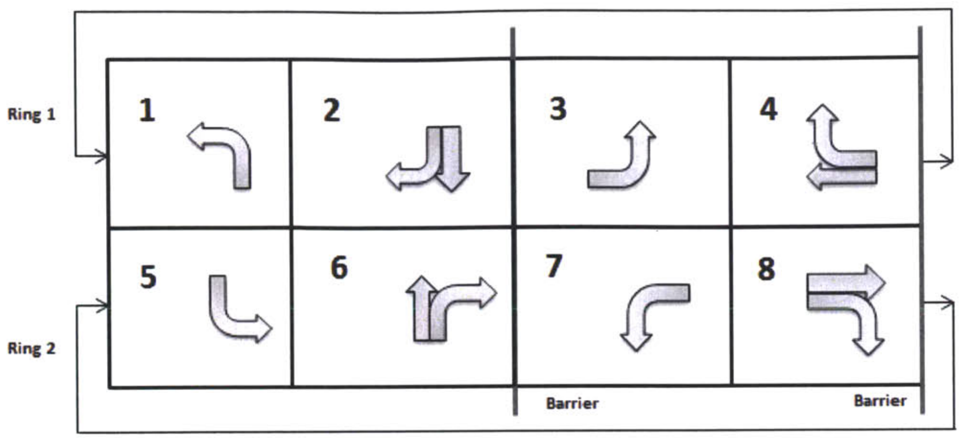


Figure 2-2: Example of ring and barrier diagram

Figure 2-2 shows the different phases organized in two continuous rings. Each ring is composed of the phases (four in this example) that can operate in a sequential order (from left to right). A barrier separates the north-south and east-west movements and also represents the end of a phase-pair. An example of a phase pair would be movements 1 and 2, or movements 3 and 4. Phase pairs that are in between barriers end at the same time. In the figure shown, phase 1 and 5 start and end at the same time, followed by phase 2 and 6, phase 3 and 7, and phase 4 and 8. After phase 4 and 8 has been completed, the cycle comes to an end and it will start again from the beginning.

This can also be explained by signal groups that depict the timing of each phase (Davol, 2001).

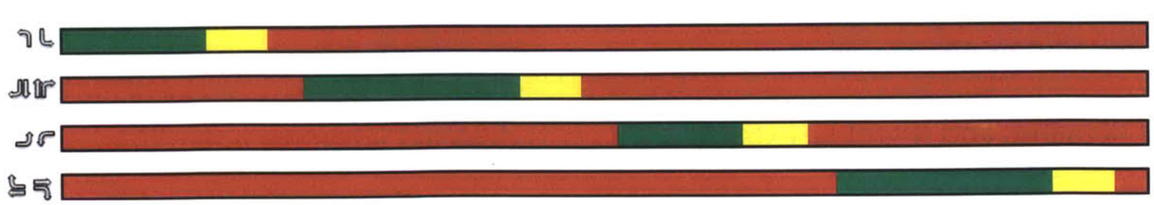


Figure 2-3: Signal group diagram

The length of the bar represents the cycle time. Phases can be understood vertically. The start of every green period corresponds to the start of the phase. For example, Phase 1 starts with the beginning of the green time and ends with the end of the all-red time of the first signal group. Phase 2 starts with the time from the beginning of the green time and ends with the end of the all red time of the second signal group. And so on.

There are three basic control types that can be used to control traffic at signalized intersections: pre-timed, actuated, or adaptive (Davol, 2001).

In pre-timed control, the cycle and the phase splits are fixed, possibly by time of day. This control type is commonly used because it is the most basic one although often it changes along the day to respond to the different traffic peaks.

In actuated control, signal timings are controlled by traffic demand, which is detected by sensors placed along the different approaches. The capability to extend the green time of a particular phase in order to accommodate more vehicles, and the capability to skip a phase in the presence of no demand are key features of actuated control. Actuated control requires a minimum green time, an extension time (which is usually the amount of time needed to cross the intersection) and a maximum green time. The minimum green time will always be provided independently of the amount of demand, and it will be extended if a car is detected when the green time remaining is less than the extension time. This can continue to occur until no additional cars are detected or until the maximum green time is reached. A phase can be skipped if there are no cars waiting for any movement associated to that phase.

Adaptive control, on the other hand, responds to traffic demand, but many more parameters are changed constantly like its cycle time and phase splits. It collects and optimizes data from the upstream approaches in order to maximize vehicle movements and minimize delays. The main features of traffic adaptive control are its capabilities of responding to random flows or irregularities, as well as to special events, incidents, and street construction. This is performed through traffic flow models that predict vehicle arrivals and adjust the timing of the plans accordingly to optimize an objective function such as total delay (Gordon and Tighe, 2005).

2.2.2 Transit Signal Priority (TSP)

Transit signal priority strategies are separated into two types: passive and active. Passive priority strategies are those in which fixed transit-weighted signal settings are used, while active priority strategies are those where dynamic detection is employed and signal settings are changed in real-time to speed up transit vehicles. Because passive priority is usually used when dwell times of transit vehicles are predictable, active priority strategies are preferred for systems such as BRTs (Skabardonis, 2000).

Passive Priority Strategies:

BRTs generally operate in complicated urban systems with severe traffic congestion and high transit demands. Passive priority is often a good alternative for reducing bus delay and travel time for public transport without the need for additional infrastructure.

Passive priority strategies facilitate movement for transit vehicles through properly coordinated signal settings, while improving bus performance. This strategy is typically simple and quick to implement as well as relatively inexpensive. Passive priority has been found to be generally effective in corridors that have a simple arterial network configuration, high bus frequencies, and predictable dwell times (Skabardonis 2000).

With passive priority, optimal signal settings are generated to minimize overall stops and delays for transit vehicles. Usually, the strategy is to either accommodate more green time to the approaches with transit vehicles by increasing the amount of time allocated to the corresponding phase, or use shorter cycles in order to minimize the waiting times of the transit vehicles at the traffic lights. The latter option, however, may have a negative effect on the intersection and result in reduced capacity and increased delays for motorists.

There are other strategies that can be used to benefit transit vehicles using the passive state, like split phasing, where the approach for the transit vehicles receives a green phase twice. Another strategy used is signal coordination, where green waves are timed using the average speed of the transit vehicles instead of the average speed of cars. This option sometimes results in increased travel times for vehicles, and may not work appropriately on routes with high dwell time variability. Although the benefits of passive priority are limited, it is sometimes the only feasible option without installation of new hardware.

It is believed that passive signal priority is not frequently used, even though they provide at least modest benefits compared to current non-optimized signal timings, and do not require any infrastructure in order to be used (Gardner et al. 2009). This strategy is very similar to signal coordination for general traffic, but used for advancing buses, which often also benefits general traffic.

Skabardonis (2000) tested various signal settings based on stop location and dwell time of the buses along an arterial in the San Francisco Bay Area. The author found that original delays experienced by buses were reduced by 14%, while the average speeds of the buses increased by 3.4%. Traffic delays at cross-streets were only increased by 1%. Overall delay for traffic moving parallel with buses was slightly decreased due to the additional green that was provided for the through traffic.

Active Priority Strategies:

Active transit signal priority strategies provide on-line priority to buses through real-time adjustment of signal timing plans. It requires sensors to detect approaching transit vehicles, as well as advanced controllers to provide priority. It adjusts the phase splits by either extending the green time for the approach with the transit vehicle, shortening the green time of the opposite approach to give an early green to the transit vehicle, skipping a phase of an opposite approach, or inserting an extra phase to permit the transit vehicle to cross the intersection. These strategies, however, affect general traffic, especially on intersections under high traffic volumes.

Figure 2-4 shows how the green interval is extended for a transit vehicle to cross the intersection, when it is detected while the green time for that approach is coming to an end.

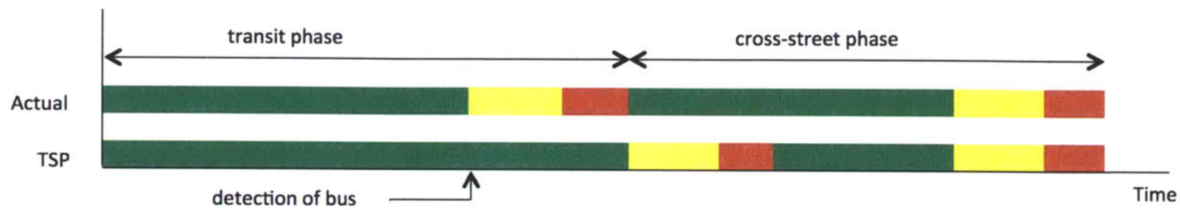


Figure 2-4: Green extension diagram

Figure 2-5 shows how the early green is applied to make a transit vehicle spend less time stopped at the intersection. This can be applied if the vehicle is detected when there is a red signal.

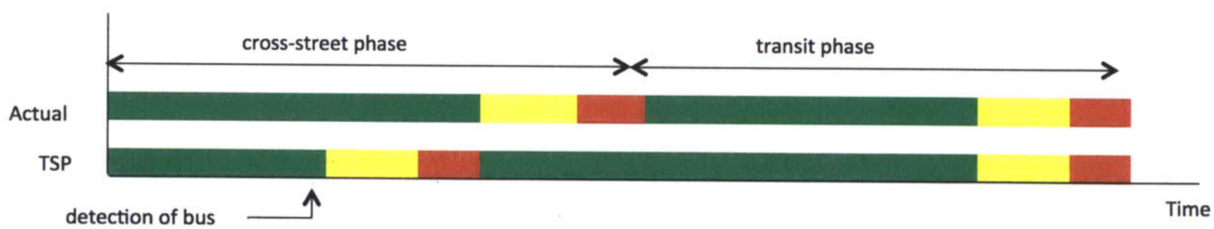


Figure 2-5: Early green diagram

If the transit vehicle is approaching a red signal, phase insertion or phase skipping could be applied. A phase would normally be inserted if the controller needs to provide priority to the vehicle before continuing with the regular plan. A phase would also be skipped if it serves movements that could be considered not critical or of low traffic volume.

Active priority is categorized as either unconditional or conditional. A strategy is unconditional if priority is provided to all transit vehicles that request it, without any consideration for their status. This may be unfavorable not only to the general traffic but also to the bus itself. For example, buses may receive priority when running ahead of schedule, allowing them to move even faster and potentially bunch with the buses ahead. However, this is sometimes the only option when buses do not have the capability to provide more information about their status.

Meanwhile, conditional priority provides priority only when certain conditions are met. The most common conditions are those which take into account schedule (if the vehicle is running late) or load (if the number of passengers on board exceeds a certain amount). However, the decision of whether to use conditional or unconditional priority depends on the goals and technologies available for implementation. This research evaluates the effectiveness of different conditional strategies because of the importance of keeping transit vehicles from traveling not only behind, but also ahead of schedule, and of minimizing the impacts on traffic by frequent priority interruptions, controlling for minimum loads on the bus.

Reserved Bus Lanes:

One of the features of Bus Rapid Transit is the implementation of its running ways. BRT running ways can vary in many levels like grade separation or lateral separation from general traffic. Running ways can be segregated, or as part of an urban street or a freeway. The American Public Transportation Association (APTA, 2010) defines the different running ways as summarized below.

Segregated running ways is the most advanced level of implementation of bus lanes, which consists of a dedicated lane that is built on its own alignment. Freeway lanes, on the other hand, are bus lanes that are part of an existing facility. These are usually in a form of a medium bus-way, which is a lane in the median of a freeway, an HOV lane, which can be located on the median or the outer lanes, or shoulder lanes, which are sometimes permitted to be used by BRT vehicles (APTA, 2010).

Urban street running ways are also implemented within the existing roadway, and can exist as median bus lanes or outer bus lanes as well, which can be shared with high occupancy vehicles, or right-turning vehicles. These can also exist as mixed-use lanes, which are used by both transit vehicles and general traffic.

There are several variations of urban street running ways that can be implemented. Some examples are peak-hour bus lanes, which are implemented only during peak periods, reversible lanes, which can provide priority in one direction during the morning and another direction during the afternoon, and bidirectional lanes, where transit vehicles are allowed to pass in one direction, while the transit vehicle waits at stations or specific areas at the other direction.

However, many land use constraints can sometimes limit the implementation of several bus-way configurations, and financial and political aspects should be considered as well. But in general, running ways are important components of BRT because they impact the operating speed, reliability, and attractiveness of the system. The higher the level of exclusive right-of-way of the bus, the faster and more reliable the service will be (APTA, 2010). The decision on which running way will be more appropriate will depend mainly on the corridor's characteristics, the areas it serves, the level of demand, the level of frequency, the funding and land constraints, and the possible environmental impacts it could have.

2.3 Literature Review on Transit Signal Priority

Transit Signal Priority has received a lot of attention in the literature, especially for conventional corridors. This section reviews the literature and lessons learned about the application of signal priority. Also, research on TSP in Bus Rapid Transit is presented.

Transit Signal Priority was introduced in the United States as early as the 1970s. Evans and Skiles (1970) found that it was an effective technique for reducing delays for transit vehicles, while resulting in several drawbacks with respect to the overall traffic. However, because of the increase in vehicle traffic and vehicular congestion, TSP implementation was rare at the time.

With the emergence of Intelligent Transportation Systems (ITS) and advances in sensor technologies, TSP witnessed increased interest in the 1990s. Many studies used microscopic simulation to evaluate different TSP concepts, since field evaluation is difficult and expensive. In general, the majority of the studies indicated that transit systems do benefit from TSP. Chang et al. (1995), for instance, report that TSP can accomplish travel time reductions of up to 42%.

Dion et al. (2004) evaluated potential TSP benefits through micro-simulation experiments on an arterial corridor in Arlington, VA. The study considered different strategies analyzing express bus service separately and express and regular bus services together. The corridor had fixed-time control, and TSP was based on green extension and early green. The authors found that, in all cases, all transit vehicles would benefit from priority, but at increased delays for traffic at cross-streets. This was particularly critical when general traffic demand was high, while under low demand, negative effects on traffic were minor as expected.

Finding a balance between transit vehicles benefiting from priority without critically worsening general traffic is an important aspect of TSP design. The motivation for conditional TSP is precisely the need to balance these two impacts. The higher the ridership, the greater the benefit for transit users, while the higher the cross-street traffic, the greater the negative impacts for general traffic.

As mentioned in the previous section, TSP can be either unconditional or conditional. Furth and Muller (2000) performed a field test in Eindhoven, Netherlands where they compared the two strategies. Results indicated that unconditional priority reduced bus travel time, but impacted the overall traffic negatively. Conditional priority, however, did increase schedule adherence and operating speed for transit vehicles, while resulting in smaller disruptions to general traffic.

Although TSP with conditional priority is generally preferred, the actual choice between conditional and unconditional depends on many factors, including costs. Xu et al. (2010) performed a comparative analysis of both types of TSP. They found that when using conditional priority, inserting a phase resulted in helping transit vehicles that were running late, but there was not much difference when the lateness condition was varied. They also found that if conditional priority could not be used, unconditional priority could help with schedule adherence when integrated with holding strategies, to account for those vehicles that are running early. The authors acknowledged the fact that it is better to use conditional priority if possible, considering that signal times are being disturbed and therefore it should be applied when necessary.

The assessment of TSP impacts is sometimes one of the most important aspects when evaluating the potential success of a TSP application. Although they evaluated TSP effects at a macro level, Skabardonis and Christofa (2011) present a methodology for estimating the impacts on Level of Service (LOS). They integrate available information such as traffic conditions, signal settings, controller actions, and frequency of transit vehicles to compare delays caused by TSP. They found that under low levels of cross-street traffic (LOS A to C), traffic conditions due to TSP stay the same, but as flow on side streets increase, TSP can worsen the current LOS by up to two levels. They compared their results as well with those from field observations and micro-simulation experiments performed along an Avenue in San Francisco, and reached similar conclusions.

Dale et al. (1999) developed a TSP assessment methodology, selecting as the main performance measures intersection delay, minor movement delay, minor movement cycle failures, bus travel time, bus schedule reliability, bus intersection delay, intersection delay per person, vehicle emissions, and accident frequency. The study showed that cross-street delays are the major concern when designing TSP. The authors also argued that simulation is a suitable method to evaluate the impacts of TSP, especially when taking into consideration the incurs in costs, risks, and study control when performing field evaluations.

Hunter (2000) also stresses the fact that cross-street delay is a major concern when applying TSP strategies. In a micro-simulation study performed along several arterials in Seattle, Washington, they found that average transit travel time and its standard deviation were shorter in all TSP evaluations. They found, however, that the success of TSP depends significantly on the number and spacing of lanes, and on traffic volumes, and that these aspects should be analyzed extensively when developing a TSP system. According to the authors, TSP will not perform well at links with more than two lanes, and at high frequency of transit service.

There are other conditions that can also affect the effectiveness of TSP. For example, Furth et al. (2010) studied the signal priority logic near bus terminals with more than one priority request per cycle from different directions. They found that by creating green waves for the buses (in order to provide priority to many at once) and minimizing the number of times a bus was stopped, bus delays could be reduced by up to 22 seconds per intersection. Although in this case the authors recommend the use of passive priority, they found that when applying green extension and early-green, they were able to reduce the initial delay that was experienced at the intersection.

Hounsel (1995) also studied the evaluation of corridors with high frequency bus services, and points out that it is a significant factor when applying TSP strategies. He studied a corridor in London that operated with headways of 60 seconds, and found that for such high frequencies, only green extension was effective. For headways shorter than 60 seconds, it was recommended to use strategies such as early-green, to better adjust the signal timing plans, but at a higher cost for cross-traffic.

2.3.1 Active TSP Implementations

There have been many field implementations of Transit Signal Priority in North America. Desphande (2003) presents a comparison of different implementations such as in Toronto where they implemented absolute TSP at 36 intersections for a light rail line in the downtown area. The goal was to reduce transit travel time and therefore total-person delays at intersections. The transit travel time reductions led to the elimination of one streetcar from the service while keeping the same frequency.

Another implementation in Snohomish County, Washington, used conditional priority based on schedule, which proved to be beneficial as well, although problems with the controllers' capabilities were experienced. In a project along a corridor in Vancouver, Canada, scheduled-based priority was also evaluated and proved effective in reducing total travel time. Its greatest benefit was reduction of the travel time variability, with a decrease in variance by an average of 59%, probably resulting in improved headway adherence.

A project in Louisiana Avenue, Minnesota, tested three different levels of signal priority - low, medium and high- where low priority applied green extension, medium priority applied a longer green extension, and high priority provided preemption (Desphande 2003). This experiment found that low and medium priority did not reduce bus travel time significantly but did not increase vehicle delays either. High priority, on the other hand, resulted in a high reduction of travel time (~38%) but also provoked an increase in average vehicle delay (23%). When analyzing total person delays, the benefits of TSP in person-hours can be significant, considering the difference in capacity of a transit vehicle versus that of a private car.

Other implementations in North Carolina, Maryland, Oregon, and Washington, have also demonstrated the effectiveness of TSP (Hunter 2000). A project in Charlotte, North Carolina was able to reduce bus travel times by 50%; Route 2 in Anne Arundel County, Maryland found travel time reductions of 16%; a project in Portland, Oregon documented travel time reductions of up to 12%; and in Pierce County, Washington, travel time reductions of up to 10% were reported. There have been other projects which have not shown any benefits - for example, an application in Pierce County, Washington - but the corridor had several intersections with critical LOS (Cims et al. 2000).

2.3.2 Signal Priority for Bus Rapid Transit Systems

As it has been mentioned in earlier sections, work to date has focused mainly on conventional bus systems, while the study of TSP for BRT corridors is still limited.

Li and Zhang (2012) performed a simulation study focused on schedule-based TSP for a BRT line in Beijing. The study applied conditional signal priority for BRT vehicles running late, as well as a holding strategy at the intersections for BRT vehicles running ahead of time, with the purpose of reducing headway variability. Results showed a more reliable service with better headway uniformity and an improved operating schedule without a significant increase in overall traffic delay.

Yang and et al. (2012) completed another study using transit speed guidance and advanced detection for implementing signal priority on a BRT corridor in Yingtan city. Transit speed guidance is a strategy used to control speed of buses for better arrival predictions. This helps to better estimate the arrival of transit vehicles at the intersections. Advanced detection, on the other hand, identifies buses that will trigger signal priority one cycle in advance. Results showed that both control strategies used to detect transit vehicles that will request priority, considerably improved the efficiency in terms of person delay, bus reliability, and impact on general traffic, in comparison with BRT features such as exclusive bus lanes and active signal priority. Signal priority using advanced detection provided the greatest benefit for the transit vehicles, while resulting in negligible impacts on general traffic, although the impact on cross-street traffic was not that much more significant when using the speed guidance strategy.

This thesis focuses on evaluating the effects of different conditional strategies on BRT operations, considering the characteristics of the intersections along the corridors, and the demand and frequencies of the BRT Systems. It also discusses the potential benefits of other transit priority strategies like signal coordination (a type of passive priority) and implementation of bus running ways along the whole corridor.

Chapter 3

Methodology

Chapter 3 presents the methodology which includes a microscopic traffic simulation approach. The description includes the simulation software used as well as the inputs and data sources needed in this thesis together with the process for the simulation experiments. Data sets provided by the relevant transit agencies are acknowledged since they allow for a more realistic representation of the scenarios to be simulated.

One of the main advantages of simulation models is the ability to provide feedback on new designs. Simulation models allow the evaluation of the efficiency of new strategies and alternative designs before they are implemented. Different simulation models permit analyses in different levels. Some provide understanding on the behavior of a system as a whole, while others provide more detailed analysis of the different entities. Microscopic simulation models, for example, can provide results that are otherwise not experimentally measurable with available technologies.

3.1 Microscopic Traffic and Transit Simulation Models

Advances in technology, especially in computer processing and software development, have led to turn traffic simulation models as part of the state-of-practice.

Simulation is a representation of the real world conditions through computer models that provide a more detailed understanding of the effects of traffic measures and strategies and their interaction with bus operations. The objective of a simulation is to test and evaluate plans and strategies before the investments are made to implement them in the field (Ratrout and Rahman, 2009).

There are two main categories of traffic simulation models: macroscopic and microscopic. Macroscopic models describe the evolution of the macroscopic velocity and the vehicle density, while microscopic models describe the movement of vehicles at the individual level including their interactions with other vehicles and with the infrastructure. There are also mesoscopic models, which consist of aspects of both macroscopic and microscopic models. Mesoscopic models describe the traffic conditions at a higher level of detail than in macroscopic models in terms of a more realistic description of the effects of congestion, but with behavior and interactions at a lower level of detail than in microscopic models (Lindgren and Tantiyanugulchai, 2003).

In the mesoscopic model, individual vehicles are simulated, but their movements come from aggregated speed-density functions instead of car-following and lane changing logics. In the macroscopic model, movement of vehicles follow volume delay functions that vary by vehicle classes and lane characteristics. The microscopic model, on the other hand, simulates vehicles every one tenth of a second, where vehicle acceleration, deceleration, car-following, lane changing, merging, yielding, and intersection movements are simulated with high detail and vary based on the vehicle's size and performance characteristics, which can be defined by the user (Ratrout and Rahman, 2009).

While macroscopic models are used mainly for the analysis of freeways (or large areas at the planning level), microscopic simulation models are used for more detailed analysis of specific corridors and complicated geometries at the operational level. Current microscopic simulation models incorporate random behavior of vehicles, together with random variation of flows. In these models, vehicles interact as they would on the actual network, responding to road geometry, interaction with other vehicles, signal controls, etc., implicitly modeling performances such as queues and shock waves.

There are several simulation softwares that can be used to model the complexity of traffic systems. Some of the most popular commercial packages are AIMSUN, VISSIM, PARAMICS, CORSIM, and TransModeler.

These commercially available microscopic packages have many common features (Ratrout and Rahman, 2009) such as:

- traffic assignment models, mesoscopic simulation models, and microscopic simulation softwares in a single software. Its microscopic simulation model generally uses car-following and lane-changing models, a pedestrian-crossing model, a passenger pick-up and drop-off model, and gap acceptance algorithms;
- a discrete, stochastic, and time-based microscopic model traffic flow simulator which contains a signal state generator (a signal control software that aggregates data on a discrete time step basis);
- distributions of driver behavior, density, peaking in demand, curbside parking, and crosswalks to appropriately represent the characteristics of a network;
- and, assignment of vehicle characteristics like speed, size, acceleration rate, minimum gap, etc., to the different modes.

TransModeler has been selected for this thesis as a simulation model that can be used at these scales: microscopic, macroscopic, and mesoscopic. It incorporates GIS capabilities that permit for easier building of big networks from GIS shape files with full integration with TransCad. It also has a 3-dimensional visualization environment that is highly advanced (Caliper, 2013).

As pointed out earlier, TransModeler is used in this research because of its microscopic characteristics, but also its transit capabilities. Its capabilities to replicate Transit Signal Priority (TSP) schemes have many advanced options, like detector-based activation or Automatic Vehicle Location (AVL) activation, as well as phase strategies like green extension, green shortening, phase-skipping, and phase calling. It also permits the application of conditional priority, allowing priority to vary by schedule and load conditions. These reasons, as well as TransModeler's capability of simulating bus and rail transit systems with headway or schedule-based services, route stops, dwell time parameters, and exclusive bus lanes, make TransModeler most appropriate for this study.

This thesis has also served to upgrade several priority features of this package in nearly real-time with the development of this research work.

3.2 Inputs and Data Sources

The following inputs were used in TransModeler to generate the scenarios to be simulated. Most of the data was provided by transit agencies' Automated Data Collection (ADC) systems and the relevant departments of transportation's information on general traffic.

3.2.1 Geometric Characteristics Network

The corridor's geometric characteristics were appropriately introduced to represent the studied corridors. Lane width, number of lanes, on-street parking, left or right turn lanes, etc., are examples of input data. Vehicle speeds are defined by the vehicle class while lane widths and posted speeds are defined by link classification (i.e. local street, freeway, etc.). These parameters come with default values typical for the U.S., which can be adjusted manually by the user.

3.2.2 Traffic Data

The traffic data needed to model the movement of vehicles on a network is entered to the model as either turning movement flows or time-variant origin-destination (O-D) trip matrices. Typically, O-D matrices come from planning models used for transportation forecasting. Turning movement flows, on the other hand, can be extracted from traffic counts.

3.2.3 Signal Timing Plans

The timing plans for the traffic signals along each were inputted to the software exactly as they were received (i.e. phase splits, cycles, offsets). These timing plans are typically available from the city's transportation department.

3.2.4 Transit Route Data

Since passenger boardings and alightings are not modeled directly in the simulations, their effect on dwell times was represented as average arrival rates and alighting percentages. This section details the necessary inputs for modeling the operation of transit routes in TransModeler.

Schedules or Average Headways:

Schedules or headway information is required to simulate transit routes. Since we are simulating BRTs, average headways were used, as these systems are characterized by having high frequencies. Average departing headways (i.e. headway between transit vehicles at first stop) and their variability (standard deviation) were used to represent bus routes.

Automatic Vehicle Location (AVL) data can be used to calculate the average departing headway and its variability. Automatic Vehicle Location systems represent one of the most useful technologies used to improve operations, providing a way to monitor and supervise buses and drivers and manage incidents, while also providing real time bus tracking.

The average departing headways were calculated using departure times at the first stop location, using the following equation:

$$\overline{H_d} = \sum (t_{n+1} - t_n) / N \qquad (1)$$

where $\overline{H_d}$ is the average departing headway, t_n is the time bus n is dispatched, and N is the number of trips analyzed.

Generally, the difference in time between bus n+1 and n is calculated and averaged along all the runs. This difference in time between two consecutive buses at the starting point of the route represents the actual departing headway. The standard deviation is used to define the variability.

$$s = \sqrt{\frac{1}{N-1}\sum((t_{n+1} - t_n) - \overline{H_d})^2} \qquad (2)$$

In this equation, s is the standard deviation, t_n is the time bus n is dispatched at the first stop, $\overline{H_d}$ is the average departing headway, and N is the number of trips analyzed.

These parameters represent important inputs for the simulation because they are representative of the conditions at the beginning of the route. However, only information on the departing headways is used, since the headways along specific points of the routes will vary according to traffic conditions.

Arrival Rates and Alighting Percentages:

Another important transit input for the simulation model is the demand for transit services measured by the average arrival rates and alighting percentages at stops. These could be estimated using data from the Automated Passenger Counting (APC) systems. Most transit agencies have, or are in the process of acquiring, Automated Passenger Counting Systems. These systems register the number of passengers that board and alight from the bus at every stop and are replacing manual methods.

APC systems count passengers in several ways. Some systems have sensors that are usually located at the front and rear doors and record the movement of passengers across an infrared beam. Other systems use treadle mats that are located on the vehicle steps and have switches that open and close when a person steps on them, determining passenger flows. APC data can also be used to determine average departing headways and their standard deviation, although most of the time these values rely on AVL records instead.

Average arrival rates at stops were estimated from APC records for the time period of interest.

Boardings per stop are estimated as:

$$\overline{B_i} = \frac{1}{N}\sum b_i \quad (3)$$

where $\overline{B_i}$ is the average boardings per trip per period for stop i, b_i is the number of boardings per trip per period at stop i, and N is the number of trips used.

Alightings per stop are estimated as:

$$\overline{A_i} = \frac{1}{N}\sum a_i \quad (4)$$

where $\overline{A_i}$ is the average alightings per trip per period for stop i, a_i is the number of alightings per trip per period at stop i, and N is the number of trips used.

Average arrivals and alightings can be used to estimate the load profile along a route in the period of interest:

$$\overline{L_i} = \overline{L_{i-1}} + \overline{B_i} - \overline{A_i} \quad (5)$$

where $\overline{L_i}$ is the average load per trip per period at stop i, $\overline{L}_{i-1}$ is the average load per trip per period at the previous stop, $\overline{B_i}$ is the average boardings per trip per period at stop i, and $\overline{A_i}$ is the average alightings per trip per period at stop i.

The average load at each stop can be used to estimate alighting percentages:

$$a_{pi} = \frac{\overline{A_i}}{\overline{L}_{i-1}} \qquad (6)$$

where a_{pi} is the alighting percentage per trip per period at stop i, $\overline{A_i}$ is the average number of alightings per trip per period at stop i, and $\overline{L}_{i-1}$ is the average load per trip per period at the previous stop.

The average boardings can be converted to arrival rates:

$$\overline{AR_i} = \overline{B_i} * n \qquad (7)$$

where $\overline{AR_i}$ is the average alighting rate per period for stop i in passengers per hour, $\overline{B_i}$ is the average boardings per trip per period at stop i, and n is the number of trips per hour per period used for stop i.

Initial Load:

If transit vehicles enter the network mid-route, another necessary input is the load at the beginning of the route, to avoid empty vehicles entering the network.

3.2.5 Vehicle Fleet Data and Dwell Time Parameters

TransModeler requires that the characteristics of the vehicle fleet be defined for each route that will be simulated, since these characteristics directly impact dwell times at stops.

Every route is assigned to a vehicle class. Every vehicle model has a defined seating capacity and total capacity (which includes standees) but also specific parameters such as dead time (i.e. time lost between the opening and closing of the doors), alighting time per passenger, boarding time per passenger, and crowding factors (i.e. additional time penalties for boarding and alighting if the bus is crowded), which vary depending on the design of the bus.

The general dwell time model used is as follows (Caliper, 2013):

$$\boldsymbol{T = \gamma + \alpha A + \beta B_0} \quad \text{if there is no crowding on the bus;} \qquad (8)$$

If the number of passengers on the bus, less the number of passengers alighting, plus the number of passengers boarding, is greater than the total seating capacity, some passengers will take longer boarding time due to crowding.

$$\boldsymbol{T = \gamma + \alpha A + \beta B_1 + (\beta + CF)B_3} \quad \text{if there is crowding on the bus} \qquad (9)$$

where:

T = total dwell time (sec)

γ = dead time (sec)

a = alighting time (sec/pas)

A = total number of passengers alighting at stop

β = boarding time (sec/pas)

B = total number of passengers boarding at stop

$B_1 = Min[\mathrm{TC} - (\mathrm{L} - \mathrm{A}), \mathrm{B}]$

$B_2 = L - A + B_1 - SC$

$B_3 = B_1 - B_2$

CF = crowding factor (sec/pas)

L = total passenger load on the vehicle upon arrival

SC = seating capacity of the vehicle

TC = total vehicle capacity

B_1 is the total number of passengers waiting to board that will be allowed to board, which will be equal to B_0 if the total passengers that will board do not exceed the remaining seating capacity. If the available seating capacity is exceeded, then the number of passengers allowed to board will be reduced to B_1. If there is crowding, some passengers (B_2) will board with little or no crowding, but once the seating capacity is reached, the remaining passengers (B_3) will take longer to board (β + CF).

3.3 Experimental Design

As stated in the introduction of this thesis, BRTs possess different characteristics that set them apart from conventional bus corridors. The main purpose of the simulation analysis is to evaluate how several TSP strategies perform under different corridor characteristics. Two case studies are used to analyze these effects, the Silver Line along Washington Street in Boston, Massachusetts, and Routes 204 and 204 express along Carmen Avenue in Santiago, Chile. Current and projected conditions are simulated, with the purpose of generating overall conclusions on how best to implement TSP based on these factors.

Four signal priority strategies were developed to account for realistic and feasible conditional strategies that could be applied in the real world. These strategies consist of a combination of headway deviation and load conditions that will decide whether a bus will be granted priority. With the headway deviation condition, priority will be granted to a bus if its headway, which is evaluated as the difference between the time of arrival of the bus that is requesting priority and the time of arrival of the previous bus at that intersection, is longer than the mean headway. The selected headway condition is of 15 seconds (i.e. priority will be granted if the headway between transit arrivals at the intersection is at least 15 seconds higher than the average design headway). This value was selected for the purpose of implementing a low threshold, as an attempt to speed up buses as soon as they begin to deviate from the design headway, while trying to avoid an increase in headways that could be difficult to recover from. However, further necessary research should be performed to assess if in fact, using such a low threshold, is a good choice.

Under the load condition, priority is granted to any bus that has a minimum number of passengers on board at the time of the request. The specific limit selected was the average load along all the stops (taken from the results calculated with equation (5)). This minimum is implemented in an attempt to reduce granting priority on all intersections along the Silver Line corridor, since the average loads seemed distributed in a way that at almost half of the stops, the bus loads were lower than the average. In Carmen Avenue, however, routes 204 and 204 express have substantially different loads throughout their trajectories, and because only one threshold can be defined for all routes, the average load was also used, to incline on granting priority mainly for 204 express vehicles, which are the ones that carry most of the load of the route.

Priority is granted in the form of green extension, red truncation, and skipping of a phase (see figures 2-4 and 2-5), with such values fixed for each intersection. The amount of time assigned for green extension was estimated using the average speed of the transit vehicles in the base case scenario, calculating the necessary time needed to cross the intersection after the vehicle is detected. A short detection distance of 100 ft from the intersection, based on TransModeler's default values, was selected to minimize the length of the time this control strategy would interrupt normal functioning of the signals. The following formula was used to estimate green extension:

$$g = {}^{d}/_{1.47\,\bar{v}} \qquad (10)$$

where g is the green extension time in seconds, d is the detection distance in feet, 1.47 is the conversion factor, and $\bar{v}$ is the average speed of the bus.

For all corridors, the amount of time the phase of the cross-street is truncated was set as half of the total green time of the cross-street. This high value was selected because of the way TransModeler deals with this parameter. In this case, the green of the cross-street will be truncated by half only if the bus is detected when the cross-street phase had just started, as shown in figure 3-1.

Figure 3-1: Maximum possible reduction of cross-street green time evaluated

If the bus is detected past the middle stage of the phase (e.g. after 20 seconds of green time, if the cross-street phase is 40 seconds) then the transit vehicle will receive no priority at all. In other words, the minimum green time for cross-traffic will always be half its phase. Therefore, if the bus is detected when the phase of the cross-street is active, the remaining green time will be shortened by the difference between half the time of the original phase and the amount of green time that has already been provided at the moment of the request. On the other hand, a phase will be skipped if its green time is less than 10 seconds.

The TSP strategies evaluated are as follow:

- "Headway deviation condition on all intersections" where priority will be granted on all intersections to a bus that is running late, according to a comparison with the headway of the previous bus. Under this logic, full priority will be tested to evaluate the benefits on transit vehicles and the impact on general traffic. On all strategies, a full cycle has to be completed before the controller can provide priority again.
- "Headway deviation and passenger load condition on all intersections" where priority will be provided to buses that are running late, according to a comparison with the headway of the previous bus, but also have a minimum number of passengers on board. This minimum is determined from the average load along the stops for each route. The logic behind this is to test the effect on transit and on general traffic of granting priority only to buses that have a given load of passengers on board.
- "Headway deviation condition on all intersections and passenger load condition on critical intersections" where priority is granted to transit vehicles that are running late, according to a comparison with the headway of the previous bus along all intersections, except on critical intersections (cross-streets with volume-to-capacity ratios (v/c) higher than 0.7) where a passenger load constraint is also applied. The threshold for passenger load is still the average load along the stops of each route. The logic behind this strategy is to try to avoid priority on intersections with high cross-street traffic, and provide priority on the rest of intersections exhibiting low to medium traffic levels.

- "Headway deviation condition on non-critical intersections and no TSP on critical intersections" where priority is provided to all transit vehicles that are running late, according to a comparison with the headway of the previous bus, except on critical intersections, where no priority will be provided. The logic for this strategy is to evaluate the benefit for transit vehicles with TSP without affecting high-volume intersections at all.

These strategies will be compared to a "Do nothing" scenario, which is the base case model which represents the conditions without any priority strategy.

Sensitivity analyses to changes in traffic and transit demands will be performed, to evaluate if the effects will change with increase in traffic flows or with higher bus frequency. These projections were only evaluated on the Boston case study, since the Santiago case study had complicated and unusual characteristics that are typically not seen in other corridors.

A scenario with increases in traffic demand of 20 percent will be examined for the Silver Line corridor to assess the effects of higher traffic volumes, and if they were sensitive to traffic demand increases, of a given level. Specific attention will be provided to the comparison of results between the four strategies, to determine if one strategy works better on a higher traffic condition than the other, and how they vary at the intersection level.

A scenario with an increase in transit demand of 15 percent will also be examined for the Silver Line corridor, to evaluate if TSP impacts will change when service frequency increases due to increased transit demand. The corresponding frequency for the increase in demand will be estimated using the boarding rate at the peak load point and an average desired load on a bus. This can be estimated using:

$$F = \frac{L_p * n}{L_d} \qquad (11)$$

where F is the new frequency of service, L_p is the new peak load, n is the previous number of trips in an hour, and L_d is the desired load on the bus.

The evaluation of the current conditions for both case studies and under scenarios with traffic and transit demand increases in the Silver Line corridor allow drawing conclusions about the effectiveness of conditional TSP strategies under low, medium, and high traffic and transit conditions. These results are tracked and compared, and general recommendations and conclusions are generated for which strategy (if any) is more appropriate depending on the corridor's characteristics.

3.4 Evaluation Metrics

In order to quantify and assess the effect of Transit Signal Priority (TSP) using the four strategies presented in the previous section, the performance measures used will be focused on statistics of travel time, delays, and headway regularity. The following specific metrics will be used:

- Travel time (for transit and private vehicles): This measure quantifies how buses are advancing due to TSP, and how private vehicles are being delayed in terms of their total trip time;
- Average speed (for transit and for private vehicles): This is another measure that quantifies if transit vehicles are being able to move faster, and how the speed of the general traffic is being impacted;
- Headway variability: This measure presents average headways between arrivals at the stops as well as their standard deviation, quantifying the impact in terms of more regular headways;
- Average total delay by intersection: Since priority strategies vary across intersections, this metric will be used to evaluate the impact of TSP strategies on overall intersection delay. Total delay by intersection is displayed as total person-hours, computed as the sum of the delay experienced over all vehicles and expanded by the corresponding average occupancy per vehicle. Average delay per vehicle will also be presented. This is estimated averaging the total delay experienced at the intersection over all the vehicles that traveled through the intersection during that interval.

Chapter 4

Boston Case Study

This chapter presents the details of the first case study used to represent the effects of signal priority on Bus Rapid Transit. It also goes into detail about the results of the strategies that were evaluated and on the performance metrics used for the analysis of these strategies.

4.1 Background

The Silver Line 5 runs along Washington Street and provides service from Dudley Square to Downtown Boston. It operates in a combined bus and right-turn only lane along most of the route, and is mixed with general traffic when it approaches the downtown area. It also uses a short segment of an exclusive contra-flow bus lane on its outbound direction.

Figure 4-1: Silver Line - Washington St. surroundings (Source: Google Maps 2013)

Silver Line 5 (SL5) is currently the only bus route that connects Dudley Station, a major bus transfer point for the areas of Roxbury and Dorchester, to the downtown area, which is also another major transfer point, and is surrounded by major business and entertainment attractions. Figure 4-1 shows the overall alignment of the Silver Line 5. The red portions indicate where a bus and right-turn only lane exists; the green portion reflects the segment with the contraflow lane (it runs in the outbound direction). Finally, the segment outlined in black delineates the portions of the route where the buses run with mixed traffic (mainly downtown area).

SL5 is a replacement of bus route 49, which consisted of a similar alignment. It implemented a new contraflow lane on the outbound direction to serve the New England Medical Center in a more direct way. The new route provided service further to the downtown area, allowing for easier transfers to the nearby subway lines.

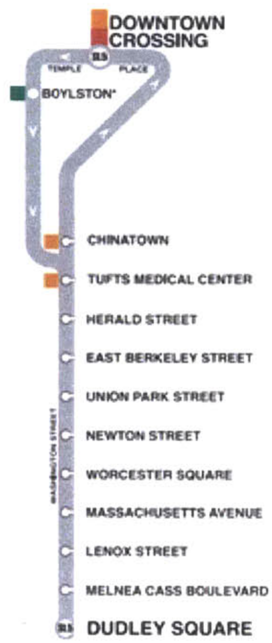


Figure 4-2: Silver Line 5 location stops (MBTA website)

Figure 4-2 shows the location of stops along Washington Street. SL5 has 12 stops in 2.3 miles, with an average distance between stops of 1/5 of a mile. It operates at 7 minute headways during the peak period and 4 to 6 trips per hour (10-15 minute headways) during the off-peak periods. Currently, the demand served in the corridor is estimated to be 15,000 passengers per weekday.

The Silver Line system has several features that categorize it as a BRT system. It has a bus lane along most of the route, as well as enhanced passenger stations and fewer stops. It also operates with 60-foot low floor articulated buses, which makes it easier (and faster) for passengers to board and alight the bus, while providing more capacity than a conventional bus. Silver Line 5 has also incorporated computer aided dispatching and automatic vehicle location systems, as well as scheduled-based conditional signal priority on four major intersections in Washington St.

Scheduled based-TSP is currently operating along Washington Street in the intersections of Melnea Cass Boulevard, Massachusetts Avenue (outbound), East Berkeley St, and Herald St. Its original operating scheme was through four complex steps that made the process of granting priority rather slow and difficult. The process started with the bus computer sending its location to MBTA's Bus Control Center, where a check was performed to identify if the bus was behind schedule. It followed with the Control Center sending a signal to the hardware at the kiosk on the side of the intersection. The hardware kiosk had to send a contact closure signal to the intersection signal controller, and the signal controller would then pass the signal to the Boston Transportation Department's (BTD) computer system. Finally, the BTD would decide if priority should be granted, in the form of green extension or early green.

A before-and-after comparison of on-time performance (OTP) of two typical days showed unclear benefits of such TSP implementation. Figures 4-3 shows the change in on-time performance of the service (before and after TSP was implemented) on an hourly basis for the inbound direction. OTP is defined by the MBTA as a headway 1.5 times higher than the scheduled one. For example, if a bus is scheduled to leave 6 minutes after the previous bus was scheduled to leave, and it leaves more than 9 minutes after, the bus is considered late.

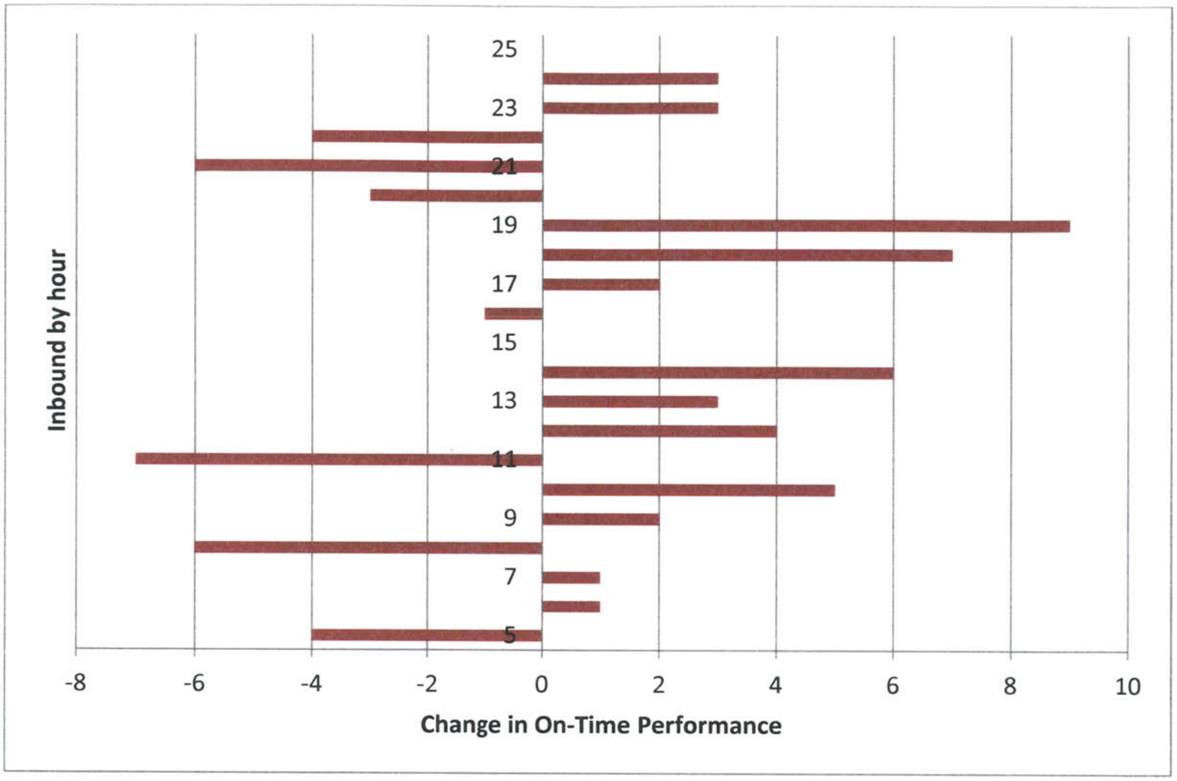


Figure 4-3: Change in on-time performance after TSP implementation

Clear fluctuations in terms of increases and decreases of on-time performance are shown in Figure 4-3 when comparing the percentages before and after TSP was implemented. For example, an average increase of 1% at 7:00 AM, and an average decrease of 6% at 8:00 AM. A possible reason for this could be the associated to the communication delay between the parties caused by the complicated scheme that is being utilized. Also, the fact that TSP is only implemented in four out of the 14 signalized intersections might explain the lack of effectiveness, especially since the route provides access to the downtown area, and in their proximity the bus lane comes to an end.

4.2 Characteristics of the Route

The period analyzed for the Silver Line 5 is the AM peak period, from 7:30 to 9:30 a.m. AVL records were obtained from the Massachusetts Bay Transportation Authority (MBTA) for a week in the Fall, from 9/18/10 to 9/24/10. The data for the weekdays was used to estimate the mean headway and its standard deviation at the beginning of the route. Table 4-1 presents a summary of these results.

Table 4-1: Mean Headway and Variability of SL5

INBOUND			OUTBOUND		
Period	Avg. Dep. H (min)	ST DEV	Period	Avg. Dep. H (min)	ST DEV
7:30-8:00	6	4.52	7:30-8:00	6	4.52
8:00-8:30	6	2.15	8:00-8:30	6	2.15
8:30-9:00	7	7.94	8:30-9:00	5	6.20
9:00-9:30	10	3.67	9:00-9:30	7	5.27

To model dwell times, passenger arrival and alighting rates were estimated using APC data from the 2012 winter period. The AM peak data was separated from the rest of the day, and the average boardings and alightings were estimated, as well as the resulting load profile which was used to convert the alighitings into percentages. Figures 4-4 through 4-7 present the average boarding and alightings per stop for both directions.

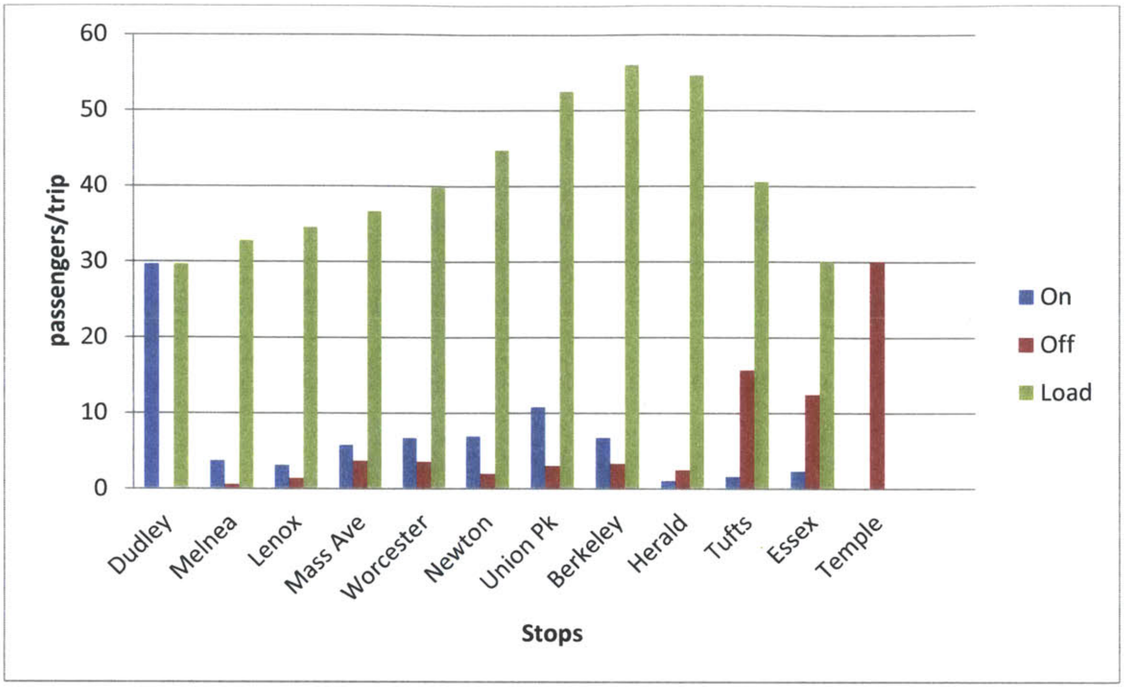


Figure 4-4: Load profile per trip for AM period 7:30-8:30 – Inbound direction

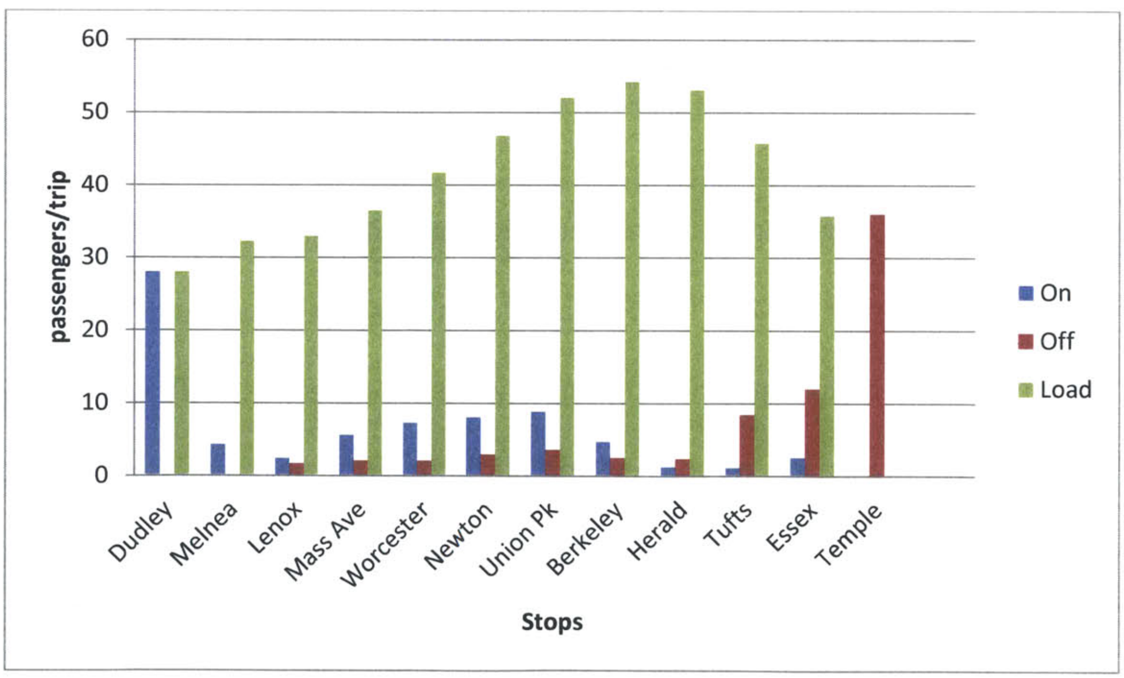


Figure 4-5: Load profile per trip for AM period 8:30-9:30 – Inbound direction

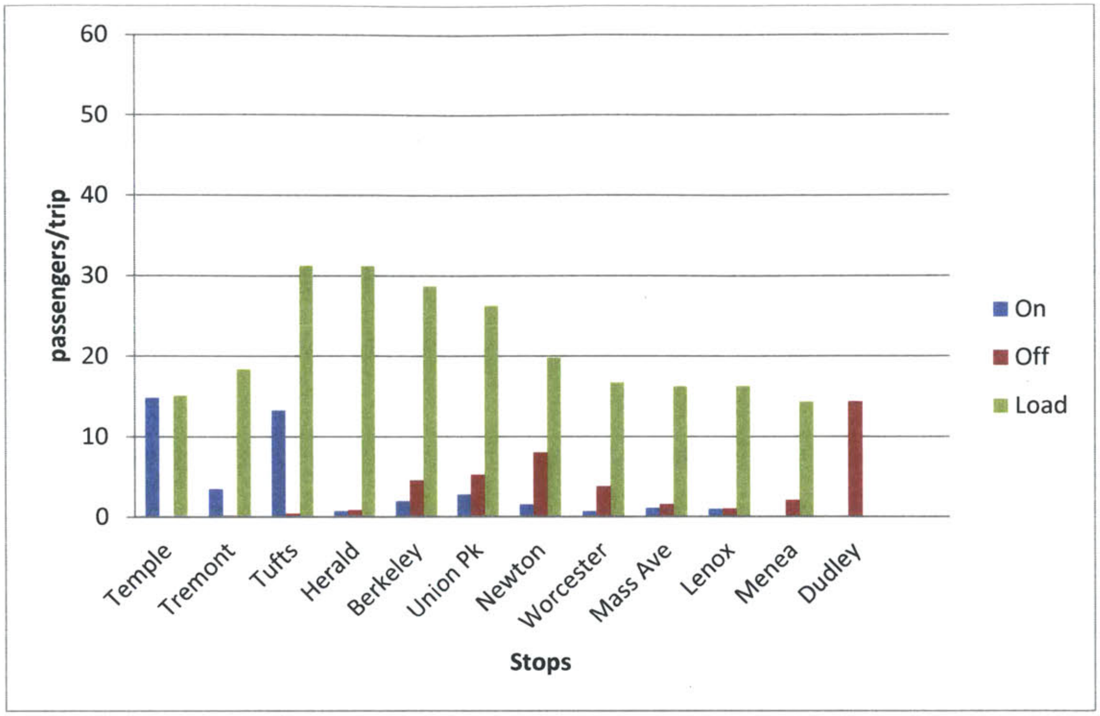


Figure 4-6: Load profile per trip for AM period 7:30-8:30 – Outbound direction

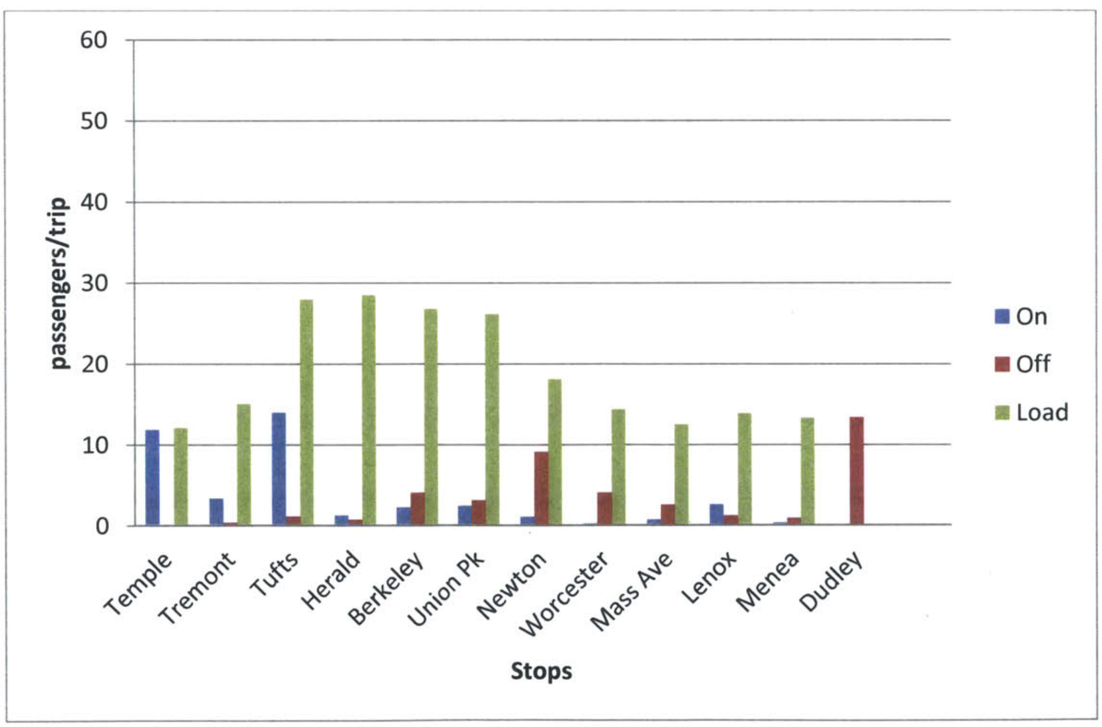


Figure 4-7: Load profile per trip for AM period 8:30-9:30 – Outbound direction

The parameters used for the dwell time model (i.e. boarding time, alighting time, and crowding factor) were taken from the default values from the Transit Capacity Manual (Hunter-Zaworski, 2003). The seating capacity, total capacity, and dead time for a low-floor CNG Neoplan bus were taken directly from the manufacturer's website. The summary of the values used for this route are presented below.

Table 4-2: Vehicle specifications and dwell time parameters

Seating Capacity	57
Total Capacity	79
Dead time (sec)	3.5
Boarding time (sec/pass)	2.2
Alighting time (sec/pass)	1.4
Crowding factor (sec/pass)	0.5

4.3 Characteristics of the Corridor

This section presents the characteristics of the corridor in terms of traffic flows and traffic signal settings.

4.3.1 Traffic Flows

In this project, traffic count studies for some intersections were provided by the Boston's Department of Transportation. Specifically, turning movement counts for some intersections were received, which represent all the movements at an intersection per vehicle class and per time period (usually every 15 minutes for a whole weekday). Therefore, results from a four-step model were also used in this corridor to estimate the missing data. Along the Silver Line corridor, turning movement flows were generated mixing the traffic volumes from the counts with the ones resulting from a four-step model of the city of Boston (Murga, 2013). This was done by generating multiplier factors from the comparison between the counts and the results from the planning model.

The resulting turning movements from the combination of the traffic counts and the flows from the planning model described in the previous chapter are summarized by link in the following figure. The map displays the generation and attraction links (in green and red respectively) during the AM peak period.

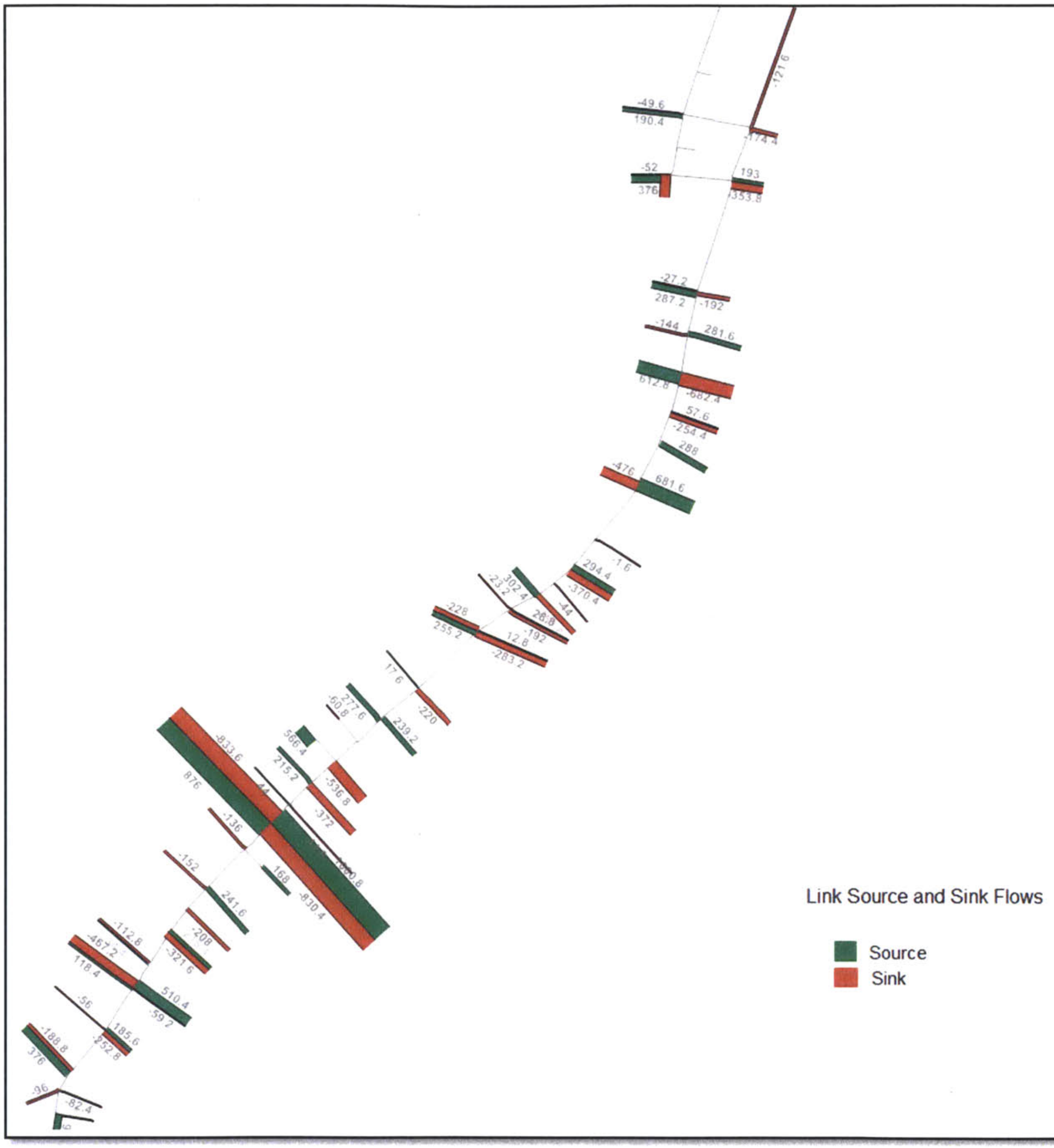


Figure 4-8: Link source and sink flows (veh/hr)

The intersections with volume-to-capacity ratios higher than 0.7 were categorized as critical intersections, and correspond to Melnea Cass, Massachusetts Avenue (Mass Ave), Berkeley St., Herald St., and Marginal St. Also, for the purpose of calculating total delay in person-hours, an average vehicle occupancy of 1.06 was considered for the state of Massachusetts, taken from the CTPP 2000 Census report (USF 2010).

4.3.2 Signal Control

Washington Street uses pre-timed signal controllers to coordinate the movements along its intersections. Of the 36 intersections the Silver Line 5 goes through, 14 are signalized. The corresponding phases, cycles and offsets are presented.

Table 4-3: Signal Timing Plans for Silver Line 5 Corridor (in seconds)

Main Street	Cross Street	Offset	Phase 1	Phase 2	Phase 3	Cycle
Washington						
	Williams	97	61	18	6	100
	Melnea Cass	6	37	40	8	100
	Mass Ave	99	31	47	7	100
	Newton	51	55	35	--	100
	Brookline	55	60	30	--	100
	Dedham	0	52	38	--	100
	Union Park	1	55	35	--	100
	Berkeley	8	43	47	--	100
	Herald	69	45	45	--	100
	Marginal	76	51	21	13	100
	Oak	83	60	30	--	100
	Kneeland	2	45	29	11	100
Tremont					--	
	Stuart	65	56	26	18	100
	Boylston	55	51	39	--	90

Generally, the first phase corresponds to the coordinated phase (or the major street), in this case Washington Street. The second phase corresponds to the cross-street movement going through and turning right and the third phase corresponds to the left turn movement. The yellow period is always 3 seconds, and the all-red period is 2 seconds. Although the corridor uses pre-timed (sequential) phases, for TSP to be able to work, signals had to be set as actuated. Therefore, maximum recall was given to all the phases, so that they will operate as though they were pre-timed.

Figure 4-9 shows the current coordination that exists along the analyzed corridor, based on the available information provided by Boston's Transportation Department (BTD) Traffic Control Center and summarized above.

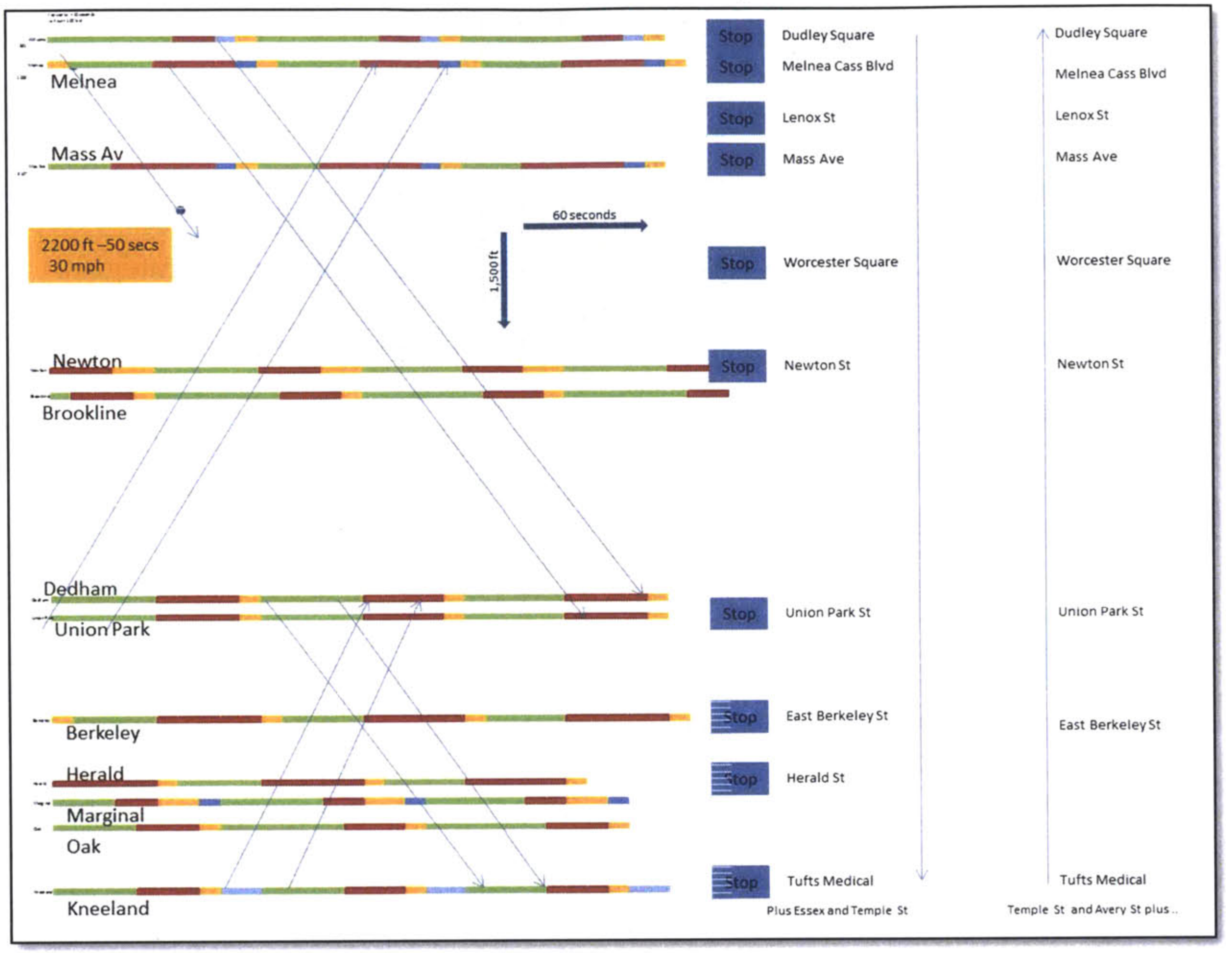


Figure 4-9: Time-space diagram (Murga, 2013)

The above space-diagram, which corresponds to a first approximation of current conditions, displays a relatively reasonable coordination along Washington street for general traffic, although it could be improved. The GPS records on the next section show the vehicular progression experienced in the afternoon through the traffic signals, along the Silver Line corridor, where stopped time for some intersections is clearly shown.

A detailed analysis is required by creating GPS records by repeated runs on board a floating car and on board the Silver Line as a passenger. A new balanced signal coordination plan may not necessarily result in very significant benefits for the Silver Line. Therefore, this analysis was based mainly on active transit priority strategies.

For this corridor, a sample of 20 replications was performed to account for the variability presented in the base case.

4.4 Data Validation

GPS records were used for partial validation of the Washington Street microscopic model. Data was collected on Sunday, May 20, 2013 for the Silver Line along Washington Street and is presented for comparison purposes to the results from the model.

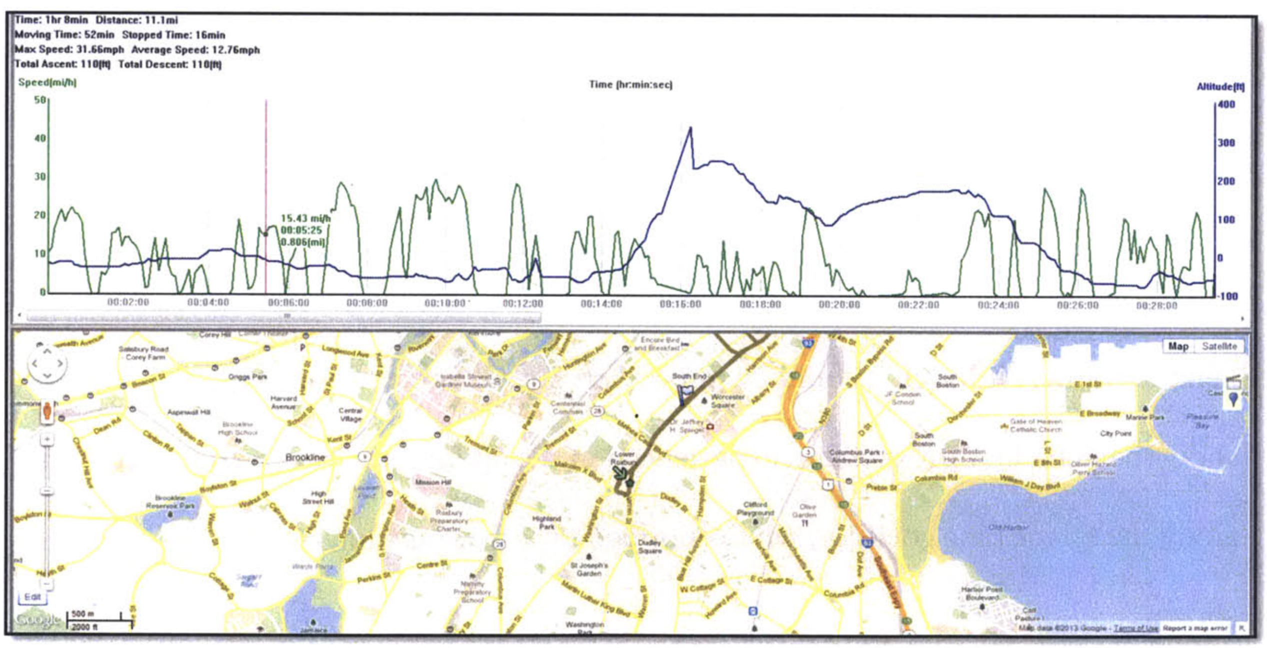


Figure 4-10: Auto speed profile from Dudley Square to Temple St.

Figure 4-10 displays the trajectory from Dudley Square to Temple street with the corresponding speed profiles recorded by the GPS in a floating car following general traffic. The vertical red line in the speed profile corresponds to the location shown with an arrow on the below's Google map. The overall average speed recorded for the segment by the GPS is 12.76 mph, which together with Google maps' route planner travel time estimate of 13 minutes for a weekday during the morning peak, is comparable to the 10.64mph average speed and 12.29 minutes observed in the Base case results from Dudley to Temple street. Given that the GPS records were recorded on a Sunday during off-peak hours, it seems reasonable to have a slightly lower speed during the morning peak on a typical weekday.

The following figures display same speed profile showing the correspondence between the speed profile (vertical red line) to the actual location (shown with an arrow). Although there are some peaks that display the stops of the vehicle, there are some segments that show continuous progress for up to two minutes.

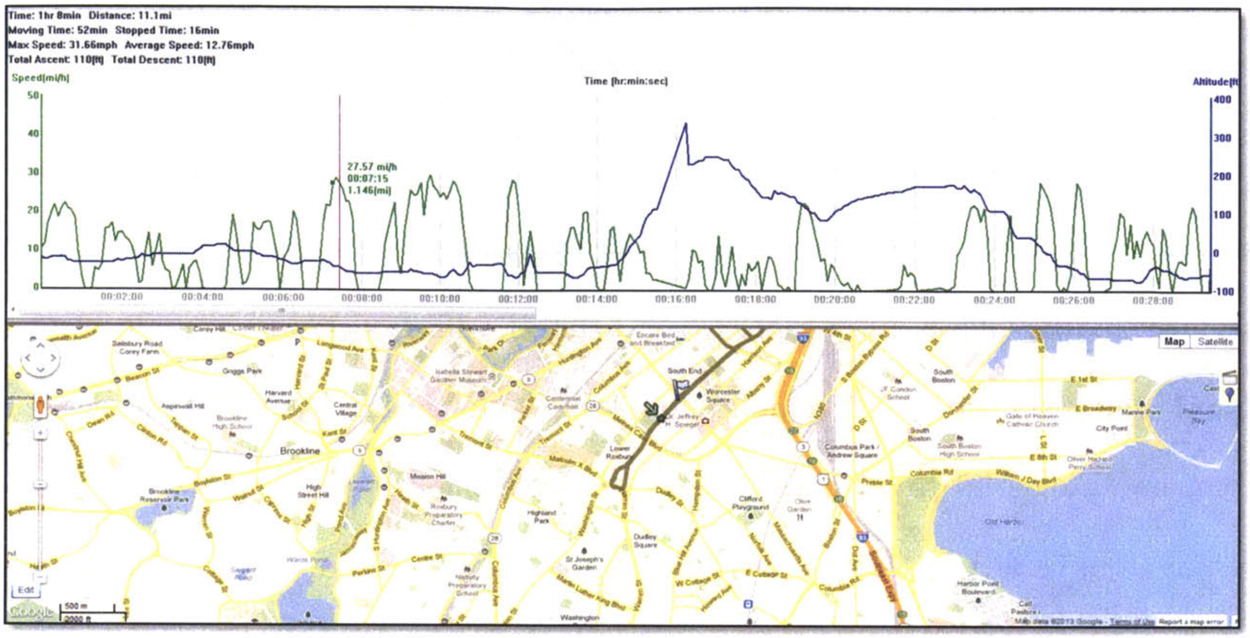


Figure 4-11: Auto speed profile relative to the location of Melnea Cass Blvd

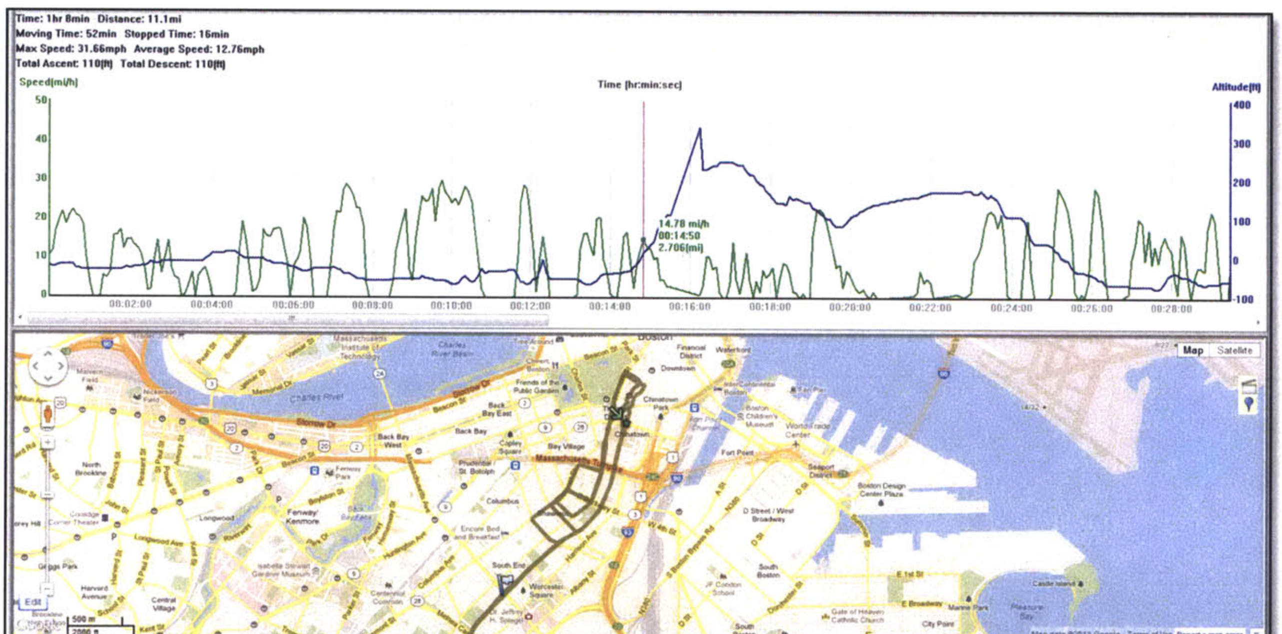


Figure 4-12: Auto speed profile associating it to the location of Tufts Medical

Figure 4-12 highlights the segment at Tufts Medical, which is where the bus lane ends. After that point, slower speeds are seen and subsequent drops in speed are noted, possibly due to the higher vehicular traffic at the downtown area, including the effect of parking maneuvers.

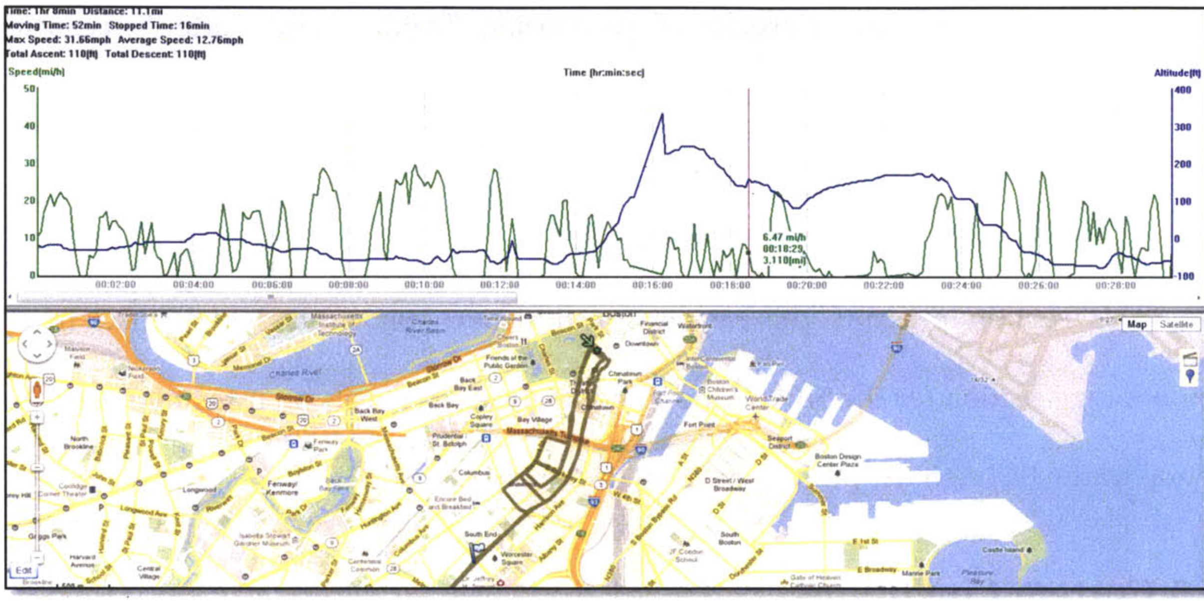


Figure 4-13: Auto Speed Profile associated to the location of the last inbound stop

Figure 4-13 highlights the segment on Temple Street, which is where the last stop is located, at a major attraction point downtown. At that point, longer periods of stopped time are noticed, since the amount of vehicular traffic, together with the traffic lights and a higher presence of pedestrians, contributes to slower movement for cars.

The behavior seen throughout the different segments helps detect the areas where higher traffic density is expected due to low speed records, and vice versa. This type of analysis of real-time speeds displayed by time and location is a very useful approach to better understand the behavior of transit and traffic vehicles along the corridor under study. Although a similar analysis for the whole day should have been performed on a weekday, there were some limitations that did not made it possible. But a similar approach is recommended for the corridor in Santiago, in order to have more realistic and detailed data to help validate the model, and furthermore, and possibly equally important, for the purpose of comparing "before" and "after" scenarios, following the eventual implementation of the recommended measures.

4.5 Evaluation of Alternative Strategies

This section presents the results for the four TSP strategies defined in the Methodology section for the Silver Line 5 and analyzes its effects on transit vehicles and general traffic through the performance metrics previously defined.

4.5.1 Current Conditions

The results of the evaluation for the current conditions are presented below. Figure 4-14 presents the average travel time and speed results for transit vehicles in the inbound direction, during the AM Peak, while Table 4-5 presents the difference of the strategies when compared to the base case.

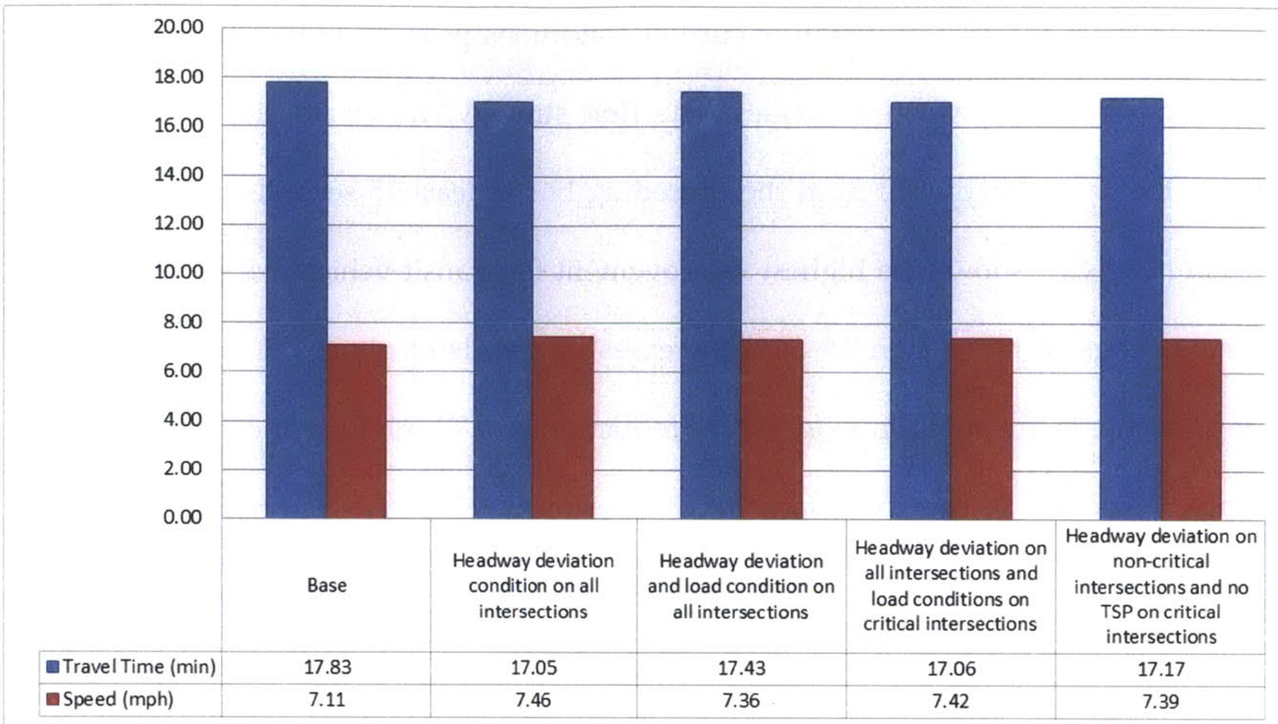


Figure 4-14: Average travel times and speeds for transit vehicles

Table 4-4: Difference and percent changes of strategies compared to Base Case

	difference in travel time (min)	% change travel time	difference in speed (mph)	% change speed
1. Headway deviation condition on all intersections	-0.77	-4.34%	0.35	4.97%
2. Headway deviation and load condition on all intersections	-0.39	-2.21%	0.25	3.47%
3. Headway deviation on all intersections and load condition on critical intersections	-0.77	-4.30%	0.31	4.33%
4. Headway deviation on non-critical intersections and no TSP on critical intersections	-0.66	-3.69%	0.28	3.96%

Results for the simulation of current conditions provide an intuitive explanation for the behavior between strategies. The first strategy, which applies priority to all buses that have headways from the preceding bus at least 15 seconds higher than the mean headway, shows the highest improvement for transit vehicles. It provides travel time savings of more than 4% and increases in speeds of about 5%. Although these improvements are small in magnitude (reduction of 0.77 minutes and increase of 0.35 mph), they could be due to the fact that SL5 performs relatively short trips.

The second strategy shows the least benefit for transit vehicles in terms of decreased travel time and increased speed (-2.21% and 3.47% respectively), since it constrains priority to the load of the bus at all intersections, and therefore less priority is provided for this case.

The third strategy showed similar results to the first strategy (-4.30% and 4.33% respectively), which is expected since in this particular case, the load is restricted at critical cross-streets, which have in average a higher load than the constraint.

The fourth strategy displays intermediate benefits (-3.69% and 3.96% respectively) when compared to the other three strategies, because it does not provide priority on critical intersections (which delays buses) with the objective of reducing the impacts to cross-streets with high levels of traffic demand.

The average headways tend to improve with the different strategies when compared to the base case, with higher improvements as the buses progress through the route and approach the downtown area. Results for average headways and its standard deviation are shown below. It is important to note that the values at the first stop probably result from the randomness of the model when simulating the vehicles at the departing terminal, with differences of less than 30 seconds, and therefore are not considered when analyzing the benefits of the strategies.

Table 4-5 and 4-6 shows the average headway at stops along the inbound direction as well as its variability.

Table 4-5: Average headway at stops along the inbound direction

Stop	Base Case	1.Headway deviation condition on all intersections	2.Headway deviation and load condition on all intersections	3.Headway deviation on all intersections and load condition on critical intersections	4.Headway deviation on non-critical intersections and no TSP on critical intersections
Dudley Sq I	6.00	5.51	5.57	5.72	5.82
Melnea Cass I	6.68	6.13	6.29	6.41	6.67
Lenox St I	6.70	6.18	6.30	6.42	6.69
Mass Ave I	6.54	6.12	6.19	6.29	6.62
Worcester I	6.49	6.15	6.14	6.28	6.57
Newton I	6.58	6.09	6.20	6.43	6.65
Union Park I	6.29	6.10	6.19	6.44	6.55
Berkeley I	6.40	6.23	6.31	6.59	6.51
Herald St I	7.18	6.53	6.61	6.68	6.82
Tufts Medical I	7.26	6.21	6.47	6.40	6.57
Chinatown I	7.44	6.19	6.26	6.48	6.57
DC I	7.19	5.95	6.02	6.24	6.32

Table 4-6: Headway standard deviation

Stop	Base Case	1.Headway deviation condition on all intersections	2.Headway deviation and load condition on all intersections	3.Headway deviation on all intersections and load condition on critical intersections	4.Headway deviation on non-critical intersections and no TSP on critical intersections
Dudley Sq I	1.47	0.74	1.06	1.14	1.76
Melnea Cass I	1.60	0.81	1.50	1.24	1.91
Lenox St I	1.61	0.83	1.50	1.24	1.92
Mass Ave I	1.56	0.87	1.55	1.43	2.08
Worcester I	1.59	0.91	1.51	1.45	2.09
Newton I	1.69	0.89	1.51	1.52	2.08
Union Park I	1.97	0.94	1.60	1.86	2.12
Berkeley I	1.75	1.11	1.70	1.88	2.23
Herald St I	2.54	1.17	1.67	1.65	2.20
Tufts Medical I	2.89	1.26	1.75	1.64	2.15
Chinatown I	2.91	1.42	1.77	1.68	2.16
DC I	2.91	1.40	1.73	1.78	2.20

The first strategy appears to be the one with the highest improvement in terms of average headway. This can also be appreciated in the reduction in headway variability. The second and third strategy display intermediate results compared to the first strategy, and have similar variability. The fourth strategy displayed higher variability compared to the rest of the strategies, and it can be explained by the fact that no priority is provided at critical intersections. Under the other strategies, priority is provided most of the time since at critical intersections buses tend to surpass the load threshold, according to the load profiles previously presented. Headway variability also increases when approaching the last stops, since right before Tufts Medical stop, the bus lane comes to an end, and buses operate under mixed- traffic conditions.

For general traffic, the results of a sample of intersections with different levels of traffic demand are presented in the following tables. Travel times and speeds for cross-streets are evaluated from the beginning of the previous intersection to the subsequent one (crossing the main corridor from the previous intersection to the next).

Table 4-7: General travel time comparison with base case

	Base Case	1.Headway deviation condition on all intersections		2.Headway deviation and load condition on all intersections		3.Headway deviation on all intersections and load condition on critical intersections		4.Headway deviation on non-critical intersections and no TSP on critical intersections	
Intersection	travel time (min)	travel time (min)	% change	travel time (min)	% change	travel time (min)	% change	travel time (min)	% change
Melnea Cass W	0.87	0.94	8%	0.92	5%	0.90	4%	0.90	3%
Berkeley W	0.68	0.76	12%	0.71	5%	0.72	7%	0.69	3%
Stuart/Kneeland E	1.37	1.47	8%	1.51	11%	1.51	11%	1.46	7%
Melnea Cass E	1.14	1.83	61%	1.88	65%	1.52	34%	1.24	9%
Washington Inbound	12.29	10.64	-13%	10.89	-11%	10.71	-13%	10.29	-16%
Union Pk W	0.78	0.84	7%	0.80	3%	0.78	0%	0.79	1%
Mass Ave E	2.94	4.22	43%	4.20	43%	4.08	38%	4.11	40%
Kneeland/Stuart W	1.53	1.66	8%	1.70	11%	1.63	6%	1.64	7%
Lenox W	0.48	0.50	3%	0.51	6%	0.48	1%	0.49	1%

Table 4-8: General traffic speed comparison with base case

	Base Case	1.Headway deviation condition on all intersections		2.Headway deviation and load condition on all intersections		3.Headway deviation on all intersections and load condition on critical intersections		4.Headway deviation on non-critical intersections and no TSP on critical intersections	
Intersection	travel time (min)	travel time (min)	% change	travel time (min)	% change	travel time (min)	% change	travel time (min)	% change
Melnea Cass W	14.05	12.98	-8%	13.40	-5%	13.53	-4%	13.62	-3%
Berkeley W	12.83	11.43	-11%	12.19	-5%	12.07	-6%	12.53	-2%
Stuart/Kneeland E	8.60	8.02	-7%	7.80	-9%	7.86	-9%	8.10	-6%
Melnea Cass E	12.56	9.27	-26%	8.24	-34%	10.08	-20%	11.52	-8%
Mass Ave W	9.15	7.52	-18%	8.77	-4%	10.58	16%	9.81	7%
Washington Inbound	10.64	11.84	11%	11.62	9%	11.75	10%	12.30	16%
Union Pk W	13.88	12.61	-9%	12.85	-7%	13.37	-4%	13.42	-3%
Mass Ave E	9.80	6.40	-35%	6.43	-34%	6.63	-32%	6.60	-33%
Kneeland/Stuart W	7.90	7.27	-8%	7.08	-10%	7.46	-6%	7.29	-8%
Lenox W	21.84	21.19	-3%	20.91	-4%	21.84	0%	21.62	-1%

Opposite to the results for the transit vehicles, the first strategy is the one that shows the highest negative impact on the general traffic on cross-streets, compared to the base case. Although the effects fluctuate, travel time increases by no more than 0.1-0.8 minutes, while average speed decreases 1-3 mph. Because some of the critical cross-streets (e.g. Melnea Cass, Mass Ave) do not show a clear behavior or follow the behavior of the rest of the cross-streets, it seems that at high-demand intersections, cross-street traffic is very sensitive to transit priority. Looking at through traffic along Washington Street (from end to end), results show that general traffic traveling along the corridor is benefitted. However, results also indicate that the highest benefits occur with the last two strategies, where the critical intersections receive limited or no priority. From the simulation results it can be seen that larger queues formed along the critical intersections, even for the through traffic in some cases, giving the impression that although some through traffic was able to benefit when transit priority was granted, the traffic that followed had to wait a little bit longer, possibly because of signal coordination being interrupted.

The above performance measures exhibit high variability for some intersections like Mass Ave and Melnea Cass Blvd. It seems that on intersections that have critical levels of service, some disturbances in the system like the interruption of the signal coordination, can result in large instabilities overall.

Table 4-9 presents the total person delay aggregated for the whole period analyzed.

Table 4-9: Total delay for the AM Peak and average delay per vehicle

	Base Case		1.Headway deviation condition on all intersections		2.Headway deviation and load condition on all intersections		3.Headway deviation on all intersections and load condition on critical intersections		4.Headway deviation on non-critical intersections and no TSP on critical intersections	
Intersection	Total Delay (person-hrs)	Avg Delay (sec/veh)	Total Delay (person-hrs)	Avg Delay (sec/veh)	Total Delay (person-hrs)	Avg Delay (sec/veh)	Total Delay (person-hrs)	Avg Delay (sec/veh)	Total Delay (person-hrs)	Avg Delay (sec/veh)
Washington & Herald	42.85	42.79	47.35	47.10	46.54	46.04	45.02	42.94	42.98	41.75
Washington & Berkeley	32.97	33.95	36.88	36.00	32.25	31.70	29.17	28.02	27.62	26.70
Washington & Union Park	7.84	12.91	8.47	13.66	8.34	12.90	8.94	13.84	8.47	13.62
Washington & Lenox	1.83	3.38	2.12	3.65	2.34	4.01	2.11	3.69	2.16	3.76
Washington & Kneeland	26.19	62.35	26.89	28.56	27.58	29.09	31.68	32.38	26.41	27.71
Tremont, Stuart & Kneeland	27.43	63.52	14.60	33.24	16.87	37.51	17.20	36.74	15.62	34.41

The first five intersections display increases in total delay during the AM peak, following the same behavior than the one displayed in the cross-street travel time results. These intersections experience in general higher delays with the first strategy (which is similar to the third strategy because of the reasons already discussed), lower delays in the second strategy, and intermediate delays with the fourth strategy, when compared with the effects of the rest. On the other hand, the last cross-street (Tremont with Kneeland/Stuart) shows reductions in delays with the TSP strategies, which is expected since in that intersection, priority is provided for transit vehicles traveling with traffic, since Tremont St. comes to an end and vehicles turn to Kneeland St. as well.

4.5.2 Sensitivity to Traffic Demand Increase

This section presents the results for the effectiveness of the four TSP strategies when there is an overall increase in traffic demand of 20%, analyzing the impacts on transit vehicles and on general traffic through the performance metrics previously defined.

Figure 4-15 presents the average travel time and speed results for the inbound direction, during the AM Peak. Table 4-10 presents the difference of effects in the strategies compared to the base case.

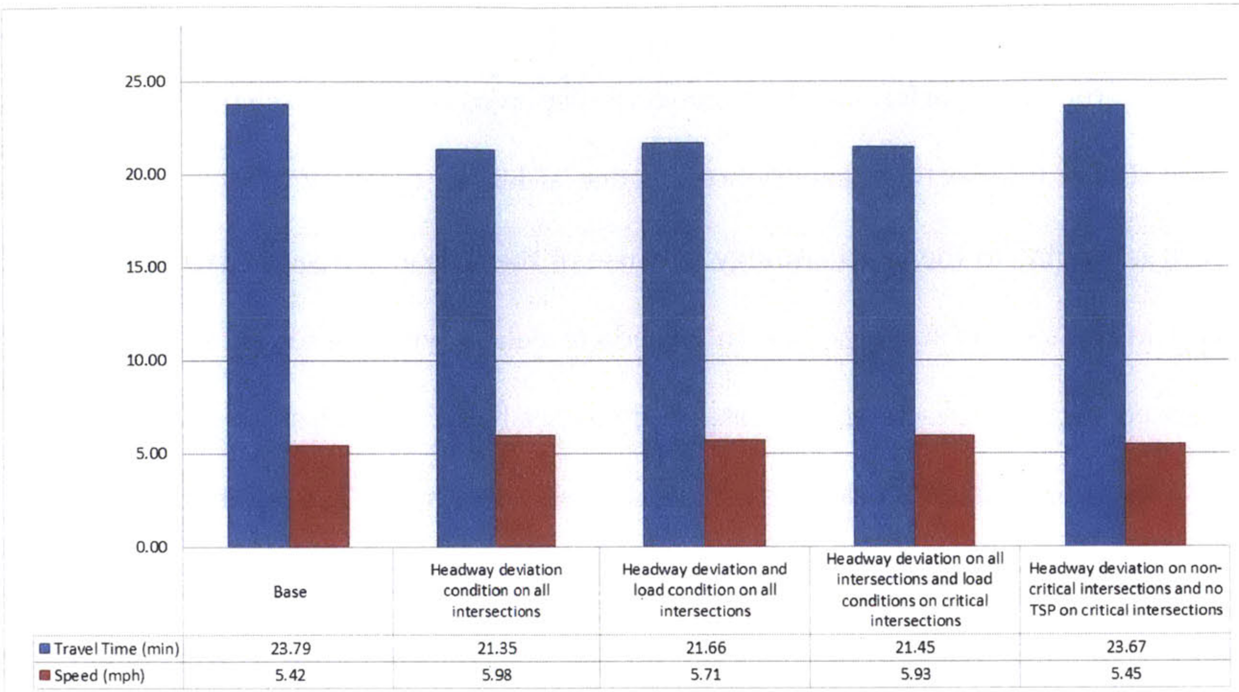


Figure 4-15: Average travel time and speeds for transit vehicles (20% traffic increase)

Table 4-10: Difference and percent changes of strategies compared to base case

	difference in travel time (min)	% change travel time	difference in speed (mph)	% change speed
1.Headway deviation condition on all intersections	-2.44	-10.27%	0.55	10.17%
2.Headway deviation and load condition on all intersections	-2.13	-8.94%	0.28	5.21%
3.Headway deviation on all intersections and load condition on critical intersections	-2.34	-9.85%	0.50	9.24%
4.Headway deviation on all intersections and no TSP on critical intersections	-0.12	-0.49%	-0.10	0.54%

Simulation results with the overall 20% increase in current traffic demand show a similar behavior for transit vehicles as before, but at a higher level when compared to the new base case. The base case's average travel time increases about 6 minutes under growing traffic demand. This increase is mostly experienced in the downtown area since it does not have a bus lane. In the bus lane section the impact is small, caused mainly by vehicles turning right. The first strategy displayed the highest benefits for transit vehicles, with a reduction in travel time of 2.4 minutes (-10%) and an increase in average speed of 0.55mph (10%). The second strategy followed the first and third strategy in order of magnitude of benefits, since it constrains priority at all intersections to a minimum load of the bus. The third strategy shows very similar results for the first strategy. This is expected since the third strategy limits priority at critical intersections only when the load on board exceeds the threshold. Load on buses at the critical intersections exceed this limit most times. The fourth strategy, on the other hand, provides no significant benefits, possibly because priority is really needed along critical intersections and in the downtown area, while the rest of the intersections do not benefit that much from priority, because they already operate in a bus lane. Although the benefits for the different strategies under the increased demand are less than the base case for the current traffic conditions, they still show moderate benefits if an increase in traffic were to occur.

Tables 4-11 and 4-12 show the average headway and variability for transit vehicles.

Table 4-11: Average headway in minutes (inbound direction)

Stop	Base Case	1.Headway deviation condition on all intersections	2.Headway deviation and load condition on all intersections	3.Headway deviation on all intersections and load condition on critical intersections	4.Headway deviation on non-critical intersections and no TSP on critical intersections
Dudley Sq I	5.59	5.51	5.14	5.84	6.01
Melnea Cass I	6.94	6.16	5.65	6.37	6.76
Lenox St I	6.95	6.18	5.65	6.38	6.86
Mass Ave I	6.91	6.17	5.66	6.18	7.07
Worcester I	6.60	6.15	5.63	6.21	6.85
Newton I	6.59	6.12	5.66	6.19	7.12
Union Park I	6.95	6.17	5.51	6.23	7.12
Berkeley I	7.64	6.88	5.85	6.85	8.66
Herald St I	8.27	7.20	6.11	7.13	9.71
Tufts Medical	8.27	6.88	5.56	6.60	9.42
Chinatown I	8.30	6.70	5.63	6.69	9.77
DC I	8.12	6.44	5.41	6.46	9.77

Table 4-12: Headway standard deviation in minutes (inbound direction)

Stop	Base Case	1.Headway deviation condition on all intersections	2.Headway deviation and load condition on all intersections	3.Headway deviation on all intersections and load condition on critical intersections	4.Headway deviation on all intersections and no TSP on critical intersections
Dudley Sq I	1.29	1.34	0.68	1.32	1.09
Melnea Cass I	2.10	1.50	0.77	1.38	1.17
Lenox St I	2.11	1.51	0.77	1.39	1.24
Mass Ave I	2.00	1.52	0.82	1.39	1.34
Worcester I	1.62	1.51	0.85	1.37	1.15
Newton I	1.69	1.56	0.79	1.43	1.48
Union Park I	2.35	1.56	0.82	1.38	1.37
Berkeley I	1.85	2.01	0.93	1.61	2.34
Herald St I	2.44	2.20	1.09	1.66	2.93
Tufts Medical	2.52	2.27	1.03	1.72	1.84
Chinatown I	2.70	2.05	1.11	1.71	2.11
DC I	2.74	2.03	1.06	1.64	2.08

Observing the average headways of the different strategies compared to the new base case, the benefits are not that clear when compared to the results for current conditions. Although there are some benefits under the first three strategies, the standard deviations are higher. The second strategy, which analyzes priority not only based on headway, but also on the bus load, proves to be the one with the greatest benefits in terms of headway distribution. The fourth strategy, on the other hand, displays higher variability towards the final stops than the base case. A possible reason for this could be that transit vehicles are advancing throughout, but suffer more stops as they approach the downtown area, as the original signal coordination is interrupted under the effects of congestion. In general, these TSP results are proving to be sensitive to the increases in demand, especially in areas that are already congested such as the downtown area whose effects are noticeable in the inbound direction.

Results of the same sample previously presented on general traffic are displayed below. Tables 4-13 and 4-14 illustrate results on travel time and speed for the general traffic.

Table 4-13: General traffic travel time comparison with base case

	Base Case	1.Headway deviation condition on all intersections		2.Headway deviation and load condition on all intersections		3.Headway deviation on all intersections and load condition on critical intersections		4.Headway deviation on non-critical intersections and no TSP on critical intersections	
Intersection	travel time (min)	travel time (min)	% change	travel time (min)	% change	travel time (min)	% change	travel time (min)	% change
Melnea Cass W	0.89	0.98	10%	0.95	7%	1.01	13%	0.92	4%
Berkeley W	0.75	0.87	15%	0.78	3%	0.81	7%	0.79	5%
Stuart/Kneeland E	1.32	1.55	17%	1.47	12%	1.53	16%	1.61	22%
Melnea Cass E	2.31	3.59	56%	3.82	65%	3.93	70%	3.33	44%
Mass Ave W	3.03	4.02	33%	3.85	27%	3.57	18%	4.63	53%
Washington I	14.43	14.10	-2%	12.46	-14%	13.48	-7%	15.25	6%
Union Pk W	0.76	0.81	7%	0.73	-3%	0.78	3%	0.88	16%
Mass Ave E	4.03	4.18	4%	4.47	11%	4.41	9%	3.91	-3%
Kneeland/Stuart W	1.54	1.71	11%	1.54	0%	1.68	9%	1.84	19%
Lenox W	1.67	1.40	-16%	1.37	-18%	1.24	-26%	1.01	-39%

Table 4-14: General traffic speed comparison with base case

	Base Case	1.Headway deviation condition on all intersections		2.Headway deviation and load condition on all intersections		3.Headway deviation on all intersections and load condition on critical intersections		4.Headway deviation on non-critical intersections and no TSP on critical intersections	
Intersection	travel time (min)	travel time (min)	% change	travel time (min)	% change	travel time (min)	% change	travel time (min)	% change
Melnea Cass W	13.74	12.56	-9%	12.87	-6%	12.22	-11%	13.23	-4%
Berkeley W	11.50	10.03	-13%	11.12	-3%	10.82	-6%	11.00	-4%
Stuart/Kneeland E	8.91	7.63	-14%	7.99	-10%	7.76	-13%	7.37	-17%
Melnea Cass E	6.58	3.82	-42%	3.55	-46%	3.79	-42%	4.28	-35%
Mass Ave W	9.73	7.03	-28%	7.47	-23%	7.86	-19%	5.83	-40%
Washington Inbound	8.94	9.07	2%	10.22	14%	9.48	6%	8.50	-5%
Union Pk W	13.57	12.91	-5%	14.22	5%	13.39	-1%	11.99	-12%
Mass Ave E	6.70	6.47	-3%	6.03	-10%	6.11	-9%	7.00	5%
Kneeland/Stuart W	7.72	7.06	-9%	7.86	2%	7.10	-8%	6.55	-15%
Lenox W	8.43	10.74	27%	12.13	44%	11.75	39%	12.70	51%

The results show significant effects on the cross-street traffic especially in critical intersections and while approaching the downtown area because of the existence of congestion and the end of the bus lane. The drastic changes in travel time and speeds illustrate the TSP impact when traffic increases by as much as 20%. However, results are not consistent or as expected. Behaviors such as reduction in travel time for Lenox Street, together with an increase in speed, and a higher impact in Melnea Cass East in the second strategy, is probably a result of an increase in traffic on intersections that were already operating under critical conditions, and as a result, present extremely variable results. This is expected considering that the increase in traffic south of downtown is accommodated in only one lane most of the time (refer to Figure 4-16), since prior to that, there is a bus reserved lane throughout, and when approaching downtown, traffic increases in an area that is already congested.

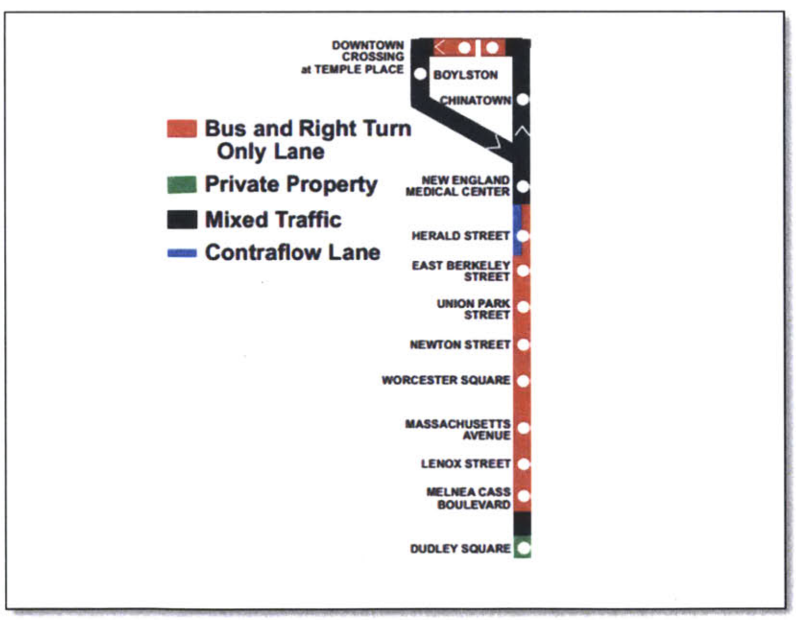


Figure 4-16: SL5 bus lanes and stops

Table 4-15: Total person delay and average vehicle delay

	Base Case		1.Headway deviation condition on all intersections		2.Headway deviation and load condition on all intersections		3.Headway deviation on all intersections and load condition on critical intersections		4.Headway deviation on all intersections and no TSP on critical intersections	
Intersection	Total Delay (person-hrs)	Avg Delay (sec/veh)	Total Delay (person-hrs)	Avg Delay (sec/veh)	Total Delay (person-hrs)	Avg Delay (sec/veh)	Total Delay (person-hrs)	Avg Delay (sec/veh)	Total Delay (person-hrs)	Avg Delay (sec/veh)
Washington & Herald	55.17	48.15	58.05	53.06	53.52	47.75	57.25	52.47	57.28	55.79
Washington & Berkeley	64.72	58.46	69.64	62.05	54.48	45.90	64.29	56.66	65.48	64.42
Washington & Union Park	10.24	14.58	10.87	15.29	9.86	13.52	11.04	15.39	12.01	20.33
Washington & Lenox	17.47	27.09	13.59	20.88	12.22	18.91	12.97	20.11	8.49	13.91
Washington & Kneeland	55.34	51.74	37.24	35.56	39.34	36.51	36.40	35.01	82.43	86.98
Tremont, Stuart & Kneeland	15.94	30.22	21.30	40.47	19.16	36.47	19.56	37.56	36.55	73.15

In this scenario of increased traffic demand, results for total delay are not consistent or as expected, and present a similar behavior as the results for travel time and speed for general traffic. These intersections display increases and decreases in total delay with the different strategies. Although the magnitude of the delay is not significant (maximum of 25 seconds additional delay per vehicle), it seems that at high-demand intersections like the ones presented in the table, which are at in the downtown area, cross-street traffic is very sensitive to transit priority and alterations to the timing plans.

4.5.3 Sensitivity to Transit Demand Increase

This section presents the results of the four TSP strategies on a scenario with 15% increase in overall transit demand, with the respective increase in frequency to keep the same quality of service as before. The new frequency for the increase in demand was estimated using the boarding rate at the projected peak load point, which was 570 passengers/hr, and an average desired load on a bus, which was set as the average load on the current base case (35 passengers). The new frequency for this scenario is 16.3 buses/hr, or 3.6 minute headways.

Figure 4-17 displays the average travel times and speeds for the transit vehicles in the inbound direction, during the AM Peak, while Table 4-15 presents the difference of results for all strategies compared to the new base case.

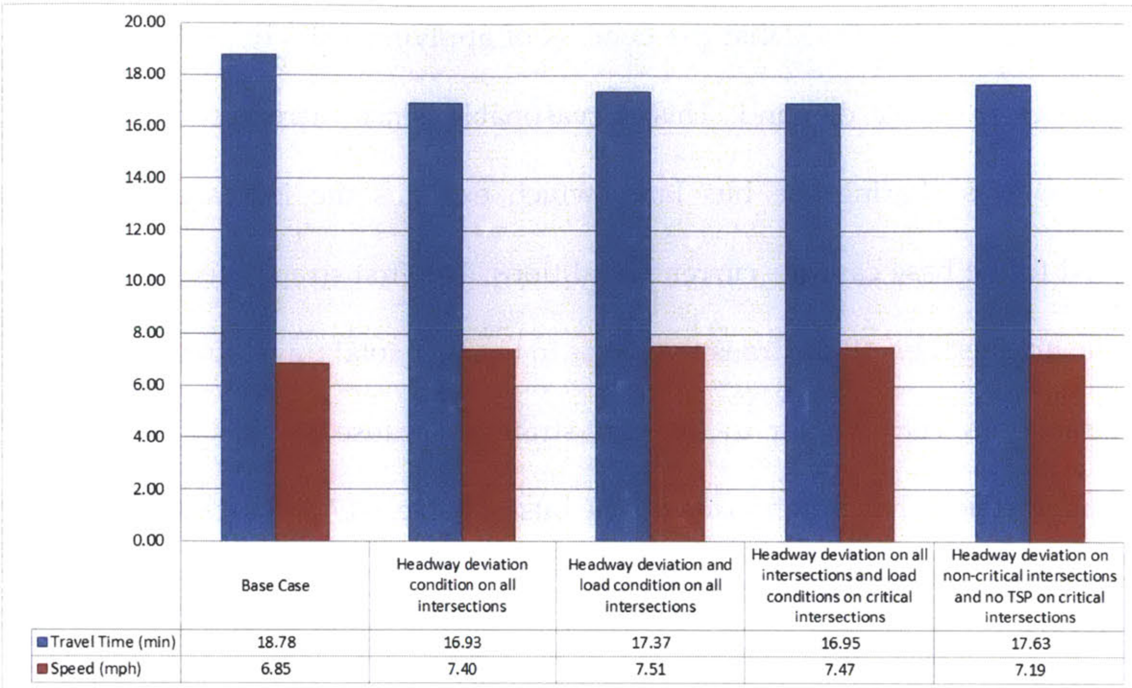


Figure 4-17: Average travel time and speeds for transit vehicles

Table 4-16: Difference and percent changes of strategies compared to base case

Base Case	difference in travel time (min)	% change travel time	difference in speed (mph)	% change speed
1.Headway deviation condition on all intersections	-1.85	-9.83%	0.55	8.03%
2.Headway deviation and load condition on all intersections	-1.40	-7.48%	0.66	9.68%
3.Headway deviation on all intersections and load condition on critical intersections	-1.83	-9.73%	0.63	9.17%
4.Headway deviation on all intersections and no TSP on critical intersections	-1.14	-6.08%	0.34	4.97%

The simulation results show that the benefits of applying TSP are higher compared to the increases in traffic demand. This is reasonable, since there are now more right-turning vehicles sharing the bus lane, which explains the increase in travel time compared to the base case for current conditions. The first strategy is still the one that offers the greatest benefit for transit vehicles in terms of total travel time and speed. The third strategy is very similar to the first strategy because for this case study, most critical intersections have high loads on the buses. Table 4-17 and 4-18 shoe the average headway and its variability at the stops

Table 4-17: Average headway at stops (min) along the inbound direction

Stop	Base Case	1.Headway deviation condition on all intersections	2.Headway deviation and load condition on all intersections	3.Headway deviation on all intersections and load condition on critical intersections	4.Headway deviation on non-critical intersections and no TSP on critical intersections
Dudley Sq I	4.50	4.29	4.45	4.43	4.19
Melnea Cass I	5.07	4.85	5.09	5.04	4.82
Lenox St I	5.09	4.86	5.09	5.05	4.83
Mass Ave I	5.08	4.78	4.99	4.96	4.74
Worcester I	5.05	4.76	4.96	4.90	4.73
Newton I	5.12	4.77	5.07	4.96	4.80
Union Park I	5.25	4.76	4.95	4.86	4.70
Berkeley I	5.32	5.04	5.10	5.00	4.93
Herald St I	5.50	5.34	5.39	5.17	5.26
Tufts Medical I	5.63	5.09	5.22	5.04	5.01
Chinatown I	5.92	5.21	5.20	5.12	5.33
DC I	5.68	4.96	4.99	4.93	5.14

Table 4-18: Headway standard deviation in minutes (inbound direction)

Stop	Base Case	1.Headway deviation condition on all intersections	2.Headway deviation and load condition on all intersections	3.Headway deviation on all intersections and load condition on critical intersections	4.Headway deviation on non-critical intersections and no TSP on critical intersections
Dudley Sq I	1.02	0.69	0.85	0.74	0.77
Melnea Cass I	1.19	0.76	0.99	0.85	0.89
Lenox St I	1.18	0.77	1.00	0.85	0.89
Mass Ave I	1.15	0.68	0.97	0.85	0.95
Worcester I	1.16	0.67	0.96	0.90	1.06
Newton I	1.20	0.68	1.12	0.92	1.13
Union Park I	1.47	0.69	1.23	1.05	1.23
Berkeley I	1.45	0.89	1.15	1.10	1.32
Herald St I	1.31	0.96	1.23	0.97	1.45
Tufts Medical I	1.46	1.05	1.16	1.15	1.40
Chinatown I	1.78	1.02	0.99	1.18	1.82
DC I	1.78	1.03	0.99	1.18	1.79

The results indicate benefits in terms of a decrease in headway variability when applying TSP. The first strategy shows the greatest improvement in general, which is similar to the third strategy, because the load threshold is exceeded at critical intersections. The fourth strategy, on the other hand, shows higher headway variability, especially towards the final stops of the route in the inbound direction, which is possibly the result of not having priority on three critical intersections while approaching the downtown area.

Table 4-19: General travel time comparison with base case

	Base Case	1.Headway deviation condition on all intersections		2.Headway deviation and load condition on all intersections		3.Headway deviation on all intersections and load condition on critical intersections		4.Headway deviation on all intersections and no TSP on critical intersections	
Intersection	travel time (min)	travel time (min)	% change	travel time (min)	% change	travel time (min)	% change	travel time (min)	% change
Melnea Cass W	0.87	0.97	12%	0.94	9%	0.95	10%	0.92	6%
Berkeley W	0.68	0.77	13%	0.71	5%	0.70	3%	0.74	9%
Stuart/Kneeland E	1.35	1.60	19%	1.51	12%	1.58	17%	1.48	9%
Melnea Cass E	0.97	2.42	148%	2.07	112%	2.14	120%	1.72	76%
Mass Ave W	3.99	3.15	-21%	3.48	-13%	3.60	-10%	2.97	-25%
Washington Inbound	12.65	11.22	-11%	10.26	-19%	10.70	-15%	10.77	-15%
Union Pk W	0.75	0.77	3%	0.80	6%	0.81	8%	0.77	3%
Mass Ave E	2.64	4.24	61%	4.13	57%	4.25	61%	4.13	57%
Kneeland/Stuart W	1.62	1.75	8%	1.68	4%	1.67	3%	1.46	-10%
Lenox W	0.54	0.50	-8%	0.49	-9%	0.48	-11%	0.50	-8%

Table 4-20: General traffic speed comparison with base case

Intersection	Base Case travel time (min)	1.Headway deviation condition on all intersections travel time (min)	1. % change	2.Headway deviation and load condition on all intersections travel time (min)	2. % change	3.Headway deviation on all intersections and load condition on critical intersections travel time (min)	3. % change	4.Headway deviation on all intersections and no TSP on critical intersections travel time (min)	4. % change
Melnea Cass W	14.08	12.59	-11%	12.99	-8%	12.96	-8%	13.30	-5%
Berkeley W	12.77	11.47	-10%	12.25	-4%	12.39	-3%	11.80	-8%
Stuart/Kneeland E	8.71	7.40	-15%	7.87	-10%	7.49	-14%	7.98	-8%
Melnea Cass E	12.78	6.33	-50%	8.02	-37%	7.92	-38%	9.02	-29%
Mass Ave W	6.74	9.21	37%	8.33	24%	8.00	19%	9.97	48%
Washington Inbound	10.28	11.31	10%	12.33	20%	11.86	15%	11.76	14%
Union Pk W	13.60	13.56	0%	12.87	-5%	12.81	-6%	13.43	-1%
Mass Ave E	10.71	6.41	-40%	6.61	-38%	6.39	-40%	6.61	-38%
Kneeland/Stuart W	7.34	6.85	-7%	7.13	-3%	7.15	-2%	8.21	12%
Lenox W	20.16	21.23	5%	21.47	6%	21.80	8%	21.43	6%

Under this scenario of 15% increase in transit demand, the impact on cross-street traffic is higher than under current conditions. The cross-streets that have low to medium levels of traffic show a similar behavior to the one displayed under current conditions, but at a slightly higher magnitude. Critical cross-streets like Melnea and Mass Ave. show mixed results, from high increase in travel times and decrease in speed, to decrease in travel times and increase in speeds. This is possibly the result of too many priority requests coinciding around the same time. Because of increase in demand, the headway between vehicles are about 3.6 minutes. With a cycle time of 100 seconds, this could create situations where a request is granted every other cycle, therefore disturbing and reducing the phases for the cross-streets frequently. The same happens to through traffic on Washington Street. Although the through traffic benefits from bus priority, the signal coordination could be disrupted, affecting individual vehicles in a random manner.

Table 4-21 displays the average person-hours delay per intersection for general traffic.

Table 4-21: Total delay for AM peak and average delay per vehicle

	Base Case		Headway deviation condition on all intersections		Headway deviation and load condition on all intersections		Headway deviation on all intersections and load condition on critical intersections		Headway deviation on non-critical intersections and no TSP on critical intersections	
Intersection	Total Delay (person-hrs)	Avg Delay (sec/veh)	Total Delay (person-hrs)	Avg Delay (sec/veh)	Total Delay (person-hrs)	Avg Delay (sec/veh)	Total Delay (person-hrs)	Avg Delay (sec/veh)	Total Delay (person-hrs)	Avg Delay (sec/veh)
Washington & Herald	43.00	42.31	46.42	44.99	42.82	44.06	42.69	42.05	45.99	45.93
Washington & Berkeley	39.32	33.95	33.06	36.00	29.27	31.70	30.22	28.02	32.41	26.70
Washington & Union Park	8.17	12.91	10.02	13.66	7.60	12.90	9.18	13.84	9.19	13.62
Washington & Lenox	2.98	3.38	2.21	3.65	2.04	4.01	2.05	3.69	2.47	3.76
Washington & Kneeland	58.27	62.35	32.42	28.56	24.69	29.09	30.19	32.38	26.16	27.71
Tremont, Stuart & Kneeland	27.34	63.52	17.89	33.24	15.34	37.51	17.88	36.74	14.39	34.41

In this scenario of increased transit frequency, results for total delay are not consistent or as expected, and present a similar behavior as the results for travel time and speed for general traffic. Intersections like Herald St. and Union Park show increase in delays, while intersections like Berkeley and Kneeland show decrease in delays. These mixed results are also displayed across the different strategies. Although the magnitude of the delay is not significant (maximum of 30 seconds of additional delay per vehicle), it seems that at high-demand intersections like the ones presented in the table, cross-street traffic is very sensitive to transit priority and alterations to the timing plans.

4.6 Other bus priority strategies

Silver Line 5 has a bus lane through most of the corridor which is shared with right-turning vehicles. The fact that the lane is shared with other vehicles, even if it is just for one movement, could limit the benefits an exclusive bus lane could bring because right-turning vehicles can delay the buses when waiting to cross. The benefit of the bus lane is also limited to the fact that it does not exist at the downtown area, which is the segment that displays more congestion. If a bus lane were to be fully implemented, either in the middle lane or in substitution of parallel parking at the streets, improved reliability should be experienced.

On the other hand, although the current signal settings display some coordination along the traffic signals, coordination could be optimized and improved to favor buses, by considering average speeds between intersections, and dwell times at stops. This priority strategy should be a first option, since it incurs in no additional equipment needed and could improve the efficiency of the system.

Chapter 5

Santiago Case Study

This chapter presents the specifics of the second case study used to evaluate the effects of signal priority for Bus Rapid Transit. It also goes into detail on the results of the strategies that were evaluated and on the performance metrics used for the analysis of such strategies.

5.1 Background

Carmen Avenue is a one-way street that runs outbound from the business district in Santiago, to the residential areas to the south. It provides critical transit service as routes 204 and 204 express (204e) connect people from the downtown area to their residential locations. The inbound portion of the route is accessed through Lira Avenue, an adjacent one-way street that begins south of Santiago and runs all the way to the downtown area.

The southern part of Santiago consists of low income residential areas (e.g. la Florida, Puente Alto, La Granja, etc.) with a high proportion of its employed residents working in the business district. Routes 204 and 204e also pass through the San Joaquin area, where the Engineering Campus of the Pontifical Catholic University of Chile is located, thus serving students as well among these areas.

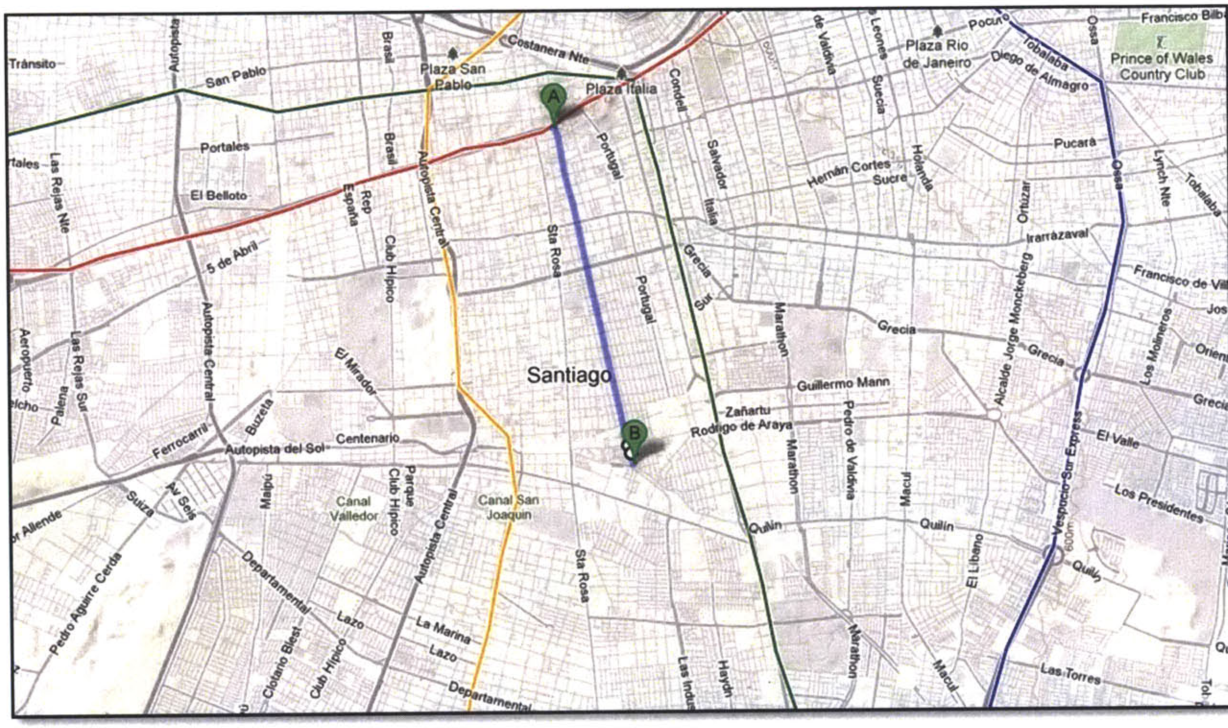


Figure 5-1: Overview of Carmen Avenue surroundings

Figure 5-1 shows an overview of the area around Carmen. The highlighted route is the portion of the corridor being analyzed. The color lines mark the underground subway system, whose Red Line connects with routes 204 and 204e in the downtown area, serving the business district.

Routes 204 and 204e are extensive in length, averaging more than 13 miles in total per direction, while serving more than 52,000 total passengers on a typical day. The outbound service starts from the Santa Lucia Metro station in Alameda Avenue, and runs through Carmen Avenue, Isabel Riquelme, Las Industrias, Yungay, Cardenal Raul Silva Henriquez, Linares, Punta Arenas, Santa Julia, Santa Raquel, Ejercito Libertador, and las Mahonias. The inbound portion runs along a similar path, from Ejercito Libertador to Santa Raquel, Santa Julia, Punta Arenas, Linares, Cardenal Raul Silva Henriquez, Yungay, Las Industrias, Sierra Bella, Lira, Curico, and Santa Rosa.

For the purpose of this study, only the Carmen portion of the outbound route will be analyzed, since it is the most congested part of the route during the PM peak (from 5:30PM to 8:30PM). This portion corresponds to the first 2.6 miles of the outbound trip, which crosses 14 signalized intersections. This portion of the route covers 13 stops for the local route, and 4 stops for the express route.

5.2 Characteristics of the Routes

Carmen Avenue has a taxi-and-bus only lane for 2.3 out of the 2.6 miles under study, which begins after the first four intersections. The reason is that it is more convenient for the buses to share the lane with taxis averaging 53 per hour during the PM Peak (Sectra-MTT report) than with the rest of the cars. This, along with the fact that the lane's designation as taxi and bus-only is not strongly enforced (i.e. some other vehicles occupy the lane as well), limits the possible benefits a bus lane could bring.

Routes 204 and 204e are peculiar routes, with many challenges that make them hard to represent. AVL and APC data was received for three weekdays representing July 2012. The analysis of the AVL data shows interesting aspects. First, although the design headway for route 204 is 4 minutes, the data showed 35 trips (instead of 45) in total for the PM period (5:30 PM - 8:30 PM), thus proving that such headway was not achieved. Because of this fact, the design headway was adjusted to 6 minutes. On the other hand, the headway between departing vehicles at the first stop showed no specific pattern. The standard deviation of the departing headways is on average 3.37 minutes. The same was noticed for route 204e. In this case, the 10 minute headway for route 204e was supposed to have scheduled 18 trips, but instead, showed an average of 11 trips. Therefore the design headway was adjusted to a more realistic value of 16 minutes. This route also showed a high standard deviation for the departing headways of 9.68 minutes.

To add complexity to this corridor, a mixture of different bus types was observed for each route, utilizing two types of rigid buses and one articulated bus. Vehicle specifications and dwell time parameters were taken from a dwell time study performed for the city of Santiago (Fernandez, 2011). The parameters used for the two vehicle classes, rigid and articulated, are summarized in Table 5-1.

Table 5-1: Dwell time parameters for Santiago based on vehicle type

Parameters	Rigid	Articulated
Seating Capacity	25	80
Total Capacity	35	135
Dead time	7.1	7.1
Boarding time (sec/pass)	1.6	1.6
Alighting time (sec/pass)	1	1
Crowding factor	0.5	0.5

The reason for having more than one vehicle type was that, since most transit bus services are contracted by the Government, the operating companies have to acquire their own bus fleet. Most of the companies that manage the bus routes in the area operate specific regions, and each company allocates the bus fleet as they see necessary. Their policy is such that there are no specific buses assigned to a specific route, but rather, buses that become available are dispatched to a route on a first-come-first-sent basis. Also, there is no specific pattern under which the buses are dispatched by the terminal (i.e. the design headways are not specifically followed, but instead a bus is sent as soon as it becomes available from a previous trip). Therefore, these routes suffer from severe bunching and missed headways.

Passenger arrival and alighting rates were estimated the same way as in the Silver Line case study.

Figure 5-2 shows the average total boardings and alightings per trip for the PM peak period.

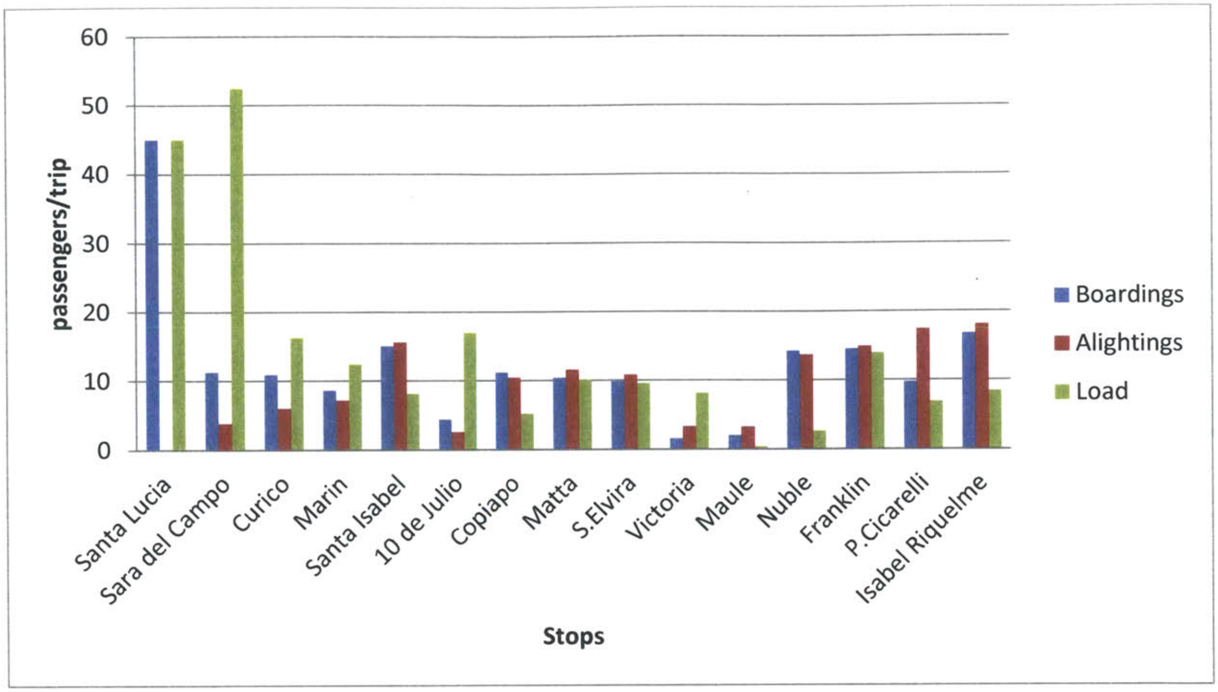


Figure 5-2: Average total boardings and alightings per trip for Route 204

Figure 5-3 shows the average boardings and alightings for route 204e.

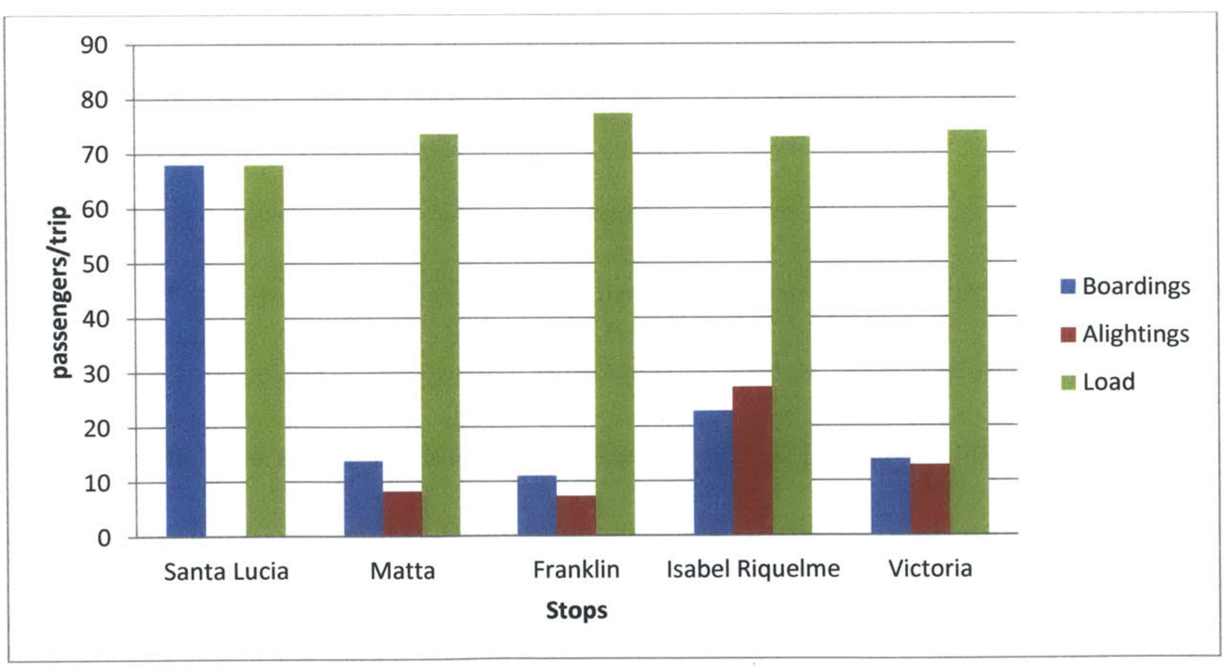


Figure 5-3 Average Total boardings and alightings for Route 204e

The first stop in the Santiago corridor is a "pay-before you board" stop (Santa Lucia). Estimations performed by the transit agency are usually unreliable when trying to approximate the number of boardings for each bus at the first stop. The logic for estimating the boardings at the first stop is to assign passengers to the first bus that departs right after they tap in at the station, using the time of the transaction from the AFC data, and the arrival time of the bus from the AVL data. However, in that specific stop, many passengers may decide not to board the first bus that arrives if they do not feel there is a guaranteed seat, given the usual bunching of buses and the frequencies of the route. Therefore, for this case, a manual count was performed during a typical weekday at the peak period to have a more realistic approximation of the initial load of the bus. The number of passengers that boarded each bus at the first stop was recorded per route, and the average of these records was used as the initial load for each route along the Carmen corridor. These initial values were presented in Figures 5-2 and 5-3 (Santa Lucia), together with the loading profile for the rest of the stops.

As the routes do not use a specific bus type, it is more complicated to represent them. Since the simulation software generates the transit trips that will be simulated before the simulation begins, vehicle classes were adjusted manually, updating the bus classification for the different trips to account for the vehicle types used for the routes along this corridor. Three base case scenarios were created for this corridor, to simulate the transit trips exactly as they had occurred on three typical weekdays, given that there is no specific pattern and that every day is different.

For this corridor, a sample of 15 replications was performed to account for the variability presented in the base case.

5.3 Characteristics of the Corridor

This section presents the characteristics of the corridor in terms of traffic flows and traffic signal settings.

5.3.1 Traffic Flows

Turning movement counts were available for all intersections of Carmen Avenue in Santiago, Chile. Specifically, turning movement counts for all the movements at an intersection per vehicle class and per time period (usually every 15 minutes for a whole weekday) were received. The resulting turning movement's flows from the traffic counts are summarized by link in Figure 5-4. The map displays the flows that are generated from a link (in green) and the flows that enter a link (red) during the PM peak period analyzed.

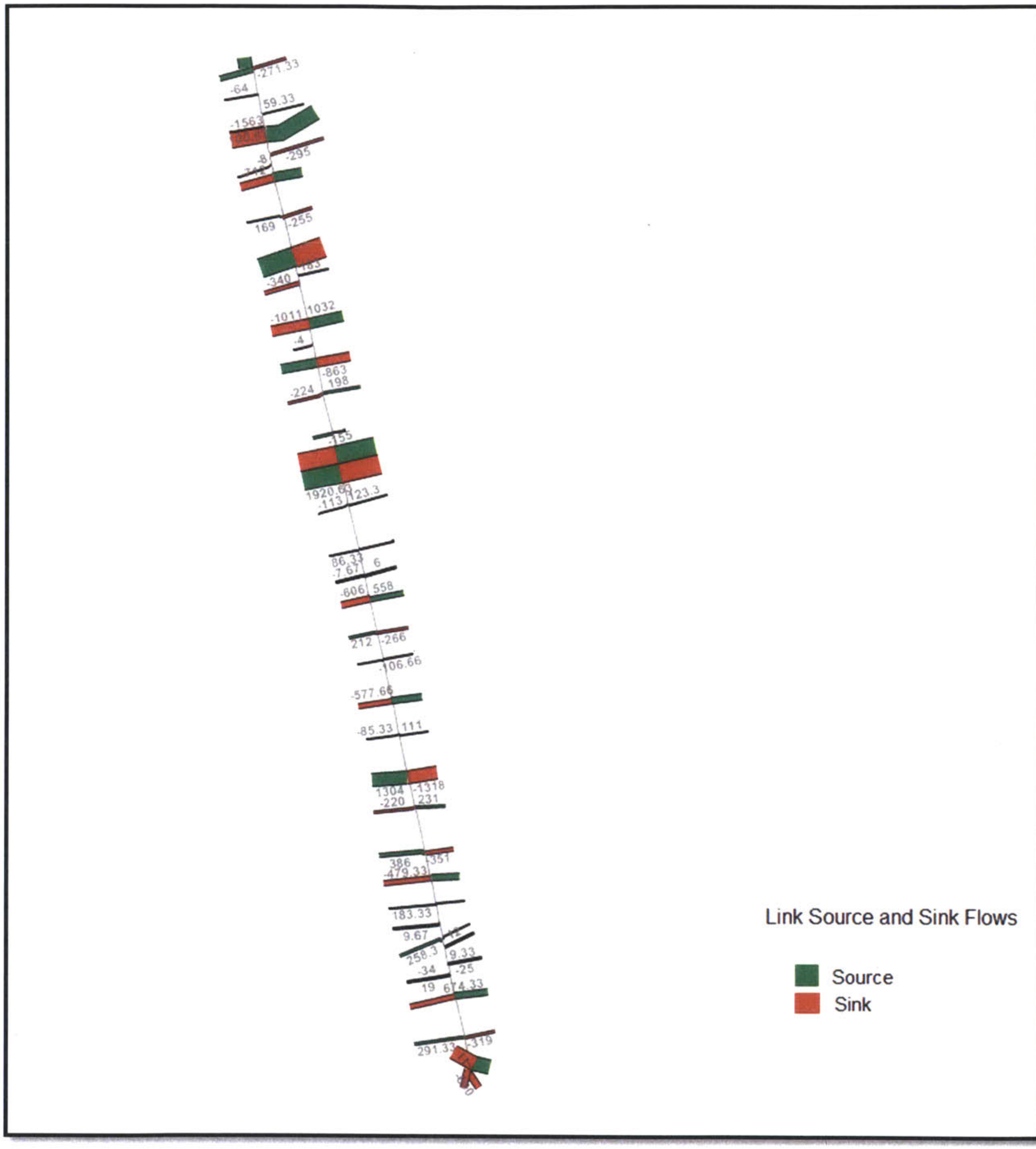


Figure 5-4: Link source and sink flows (veh/hr)

The intersections with volume-to-capacity ratios higher than 0.7 were categorized as critical intersections, and correspond to Nuble, Matta, Santa Isabel, and Curico, which carry more through traffic than Carmen itself. Also, for the purpose of estimating the total delay per intersection (person-hrs), an average vehicle occupancy of 1.25 was used (Ortuzar, 2002).

5.3.2 Signal Control

Carmen Avenue uses pre-timed signal controllers to coordinate the movements along its intersections. Of the 39 intersections in the Carmen segment, 14 are signalized. The corresponding phases, cycles and offsets for each were inputted as received by Santiago's Transportation Department (SECTRA), and are presented below.

Table 5-2: Signal Timing Plans for Carmen Avenue intersections

Signal Timing Plans					
Cross Street	Offset	Phase 1	Phase 2	Phase 3	cycle
Marcoleta	96	56	34	--	100
Curico	22	41	49	--	100
Marin	99	60	30	--	100
Santa Isabel	32	44	46	--	100
Argomedo	17	61	29	--	100
10 julio	13	48	42	--	100
Copiapo	5	53	37	--	100
Matta	7	46	50	9	120
Victoria	2	44	32	--	86
Pedro Lago	16	60	16	--	86
Maule	17	43	33	--	86
Nuble	15	28	48	--	86
Franklin	9	37	39	--	86
P. Cicarelli	3	34	43		86

Generally, the first phase corresponds to the coordinated phase (or the major street), in this case Carmen Avenue. The second phase corresponds to the cross-street movement going through and turning right, and the third phase corresponds to the left turn movement. The yellow interval after each phase is always 3 seconds, and the all-red period is 2 seconds. As mentioned in the Boston case study, signals had to be set as actuated for TSP to be able to work. Therefore, maximum recall was given to all the phases, so that they will operate as though they were pre-timed.

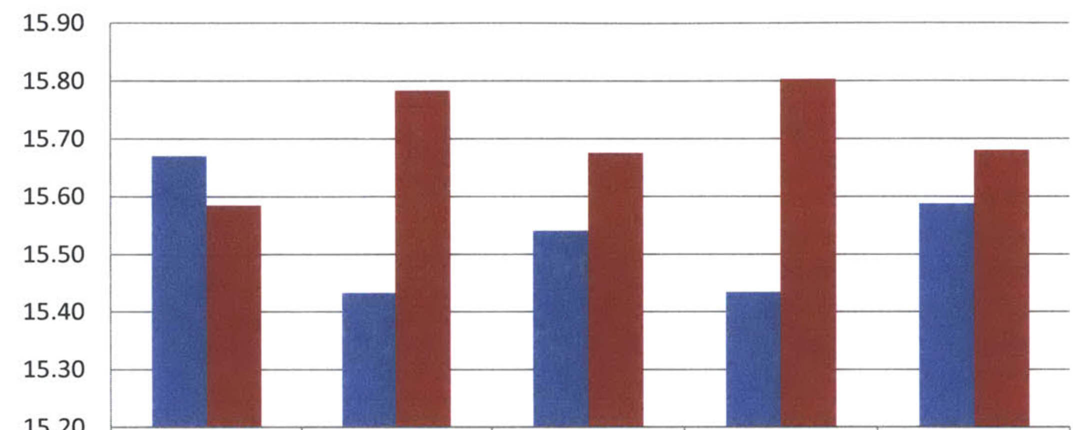
5.4 Validation

The simulation model of the corridor has a number of limitations compared to the actual condition. The corridor has a number of unique characteristics that are difficult to replicate. The weak enforcement of the bus-and-taxi lane results in the orridor being used frequently by general traffic, to escape the congestion of other lanes during the peak periods. Also, the fact that there are no specific buses assigned to each route, and instead, buses are dispatched as they become available (i.e. headways are not specifically followed) makes it difficult to represent this corridor.

The traffic counts received for this corridor was the only data available (since no planning model results were available) and their accuracy is questionable. As a result, travel times are slightly lower for general traffic and 4-5 minutes higher for transit vehicles in reality, compared to the simulation. In this context, this model could serve to provide clues on the level of lane enforcement effectiveness.

5.5 Analysis of Results

This section presents the results for the four TSP strategies on the Carmen corridor and analyzes their impact on transit vehicles and general traffic.



	Base	Headway deviation condition on all intersections	Headway deviation and load condition on all intersections	Headway deviation on all intersections and load conditions on critical intersections	Headway deviation on non-critical intersections and no TSP on critical intersections
Travel time (min)	15.67	15.43	15.54	15.44	15.59
Speed (mph)	15.58	15.78	15.68	15.80	15.68

Figure 5-5: Average travel time and speeds for transit vehicles

Figure 5-5 presents the average travel time and speed results for the transit vehicles. One has to consider that a limitation of the simulation software is that it does not differentiate basic statistics like travel time and speed per route. The results shown in Figure 5-5 are the average values for all transit vehicles (and for both routes). Therefore, route 204 should have higher travel times and lower speed values since it is a local route with 17 stops, while for route 204e, travel times should be lower and speed values should be higher, since it is an express service with only 4 stops.

Table 5-3: Difference and percent changes of strategies compared to base case

Strategies	difference in travel time (min)	% change travel time	difference in speed (mph)	% change speed
Headway deviation condition on all intersections	-0.24	-1.51%	0.20	1.27%
Headway deviation and load condition on all intersections	-0.13	-0.83%	0.09	0.58%
Headway deviation on all intersections and load conditions on critical intersections	-0.24	-1.50%	0.22	1.40%
Headway deviation on non-critical intersections and no TSP on critical intersections	-0.08	-0.52%	0.10	0.61%

Results from the simulation of current conditions along Carmen Avenue show a behavior similar than the Silver Line corridor. The first strategy, where only the headway condition is applied, displays the highest improvement in travel time and speeds for transit vehicles. Results for this scenario are very similar to the third strategy. The difference between the first and third strategies is not that significant, possibly due to the fact that the most frequent route (204 local) has low passenger loads throughout, and the average is skewed by the high loads of 204e, which only stops along four stops. Also, because bunching was a common problem for the base case, there are many priority requests that are not granted, and therefore the average bus travel time increases on all strategies (i.e bunching is probably being reduced, which results in larger headways). The fourth strategy showed the least improvement, possibly because in this strategy, all of the 204e runs did not receive priority, as was not the case in the third strategy. The second strategy displayed intermediate results between the other strategies. But because of the particular situation of this corridor, where there is severe bunching and loads vary considerable between routes, the effects of TSP cannot be appreciated without looking at the variability of the headways.

Table 5-4: Average headway at stops

	Stop	Base Case	1.Headway deviation condition on all intersections	2.Headway deviation and load condition on all intersections	3.Headway deviation on all intersections and load condition on critical intersections	4.Headway deviation on non-critical intersections and no TSP on critical intersections
204	Pintor Cicarelli	7.99	8.86	8.25	8.56	9.41
204	Franklin	7.98	8.98	8.11	8.56	9.39
204	Nuble	7.99	8.99	8.65	8.50	9.36
204	Maule	8.14	9.17	8.79	8.64	9.51
204	Victoria	8.12	9.04	8.92	8.64	9.51
204	Santa Elvira	8.02	8.90	8.77	8.52	9.41
204	Matta	7.95	8.89	8.79	8.35	9.37
204	Copiapo	7.95	8.90	8.79	8.35	9.35
204	Av. 10 de Julio	7.97	8.98	8.83	8.45	9.50
204	Marin	7.92	8.83	8.53	8.31	9.51
204	Sara del Campo	8.04	8.76	8.27	8.67	9.26
204	Isabel Riquelme	7.95	8.83	8.18	8.52	9.27
204e	Pintor Cicarelli	22.39	31.10	27.19	26.96	32.67
204e	Victoria	25.50	31.18	33.11	24.11	32.51
204e	Matta	24.68	30.52	32.13	23.63	31.18
204e	Marin	24.84	29.85	34.45	24.16	28.71

Looking at average headways between arrivals at the stops, we can observe that the average headways start to increase with TSP. This is specific for a city like Santiago where the headways are not enforced (vehicles are dispatched when they become available) and therefore the bunching effect is highly present. It is important to remember that route 204 and 204e have headways of 6 and 16 min respectively, with standard deviations of 3.4 and 9.68 minutes respectively. Although it is difficult to confirm each vehicle's behavior, it seems like overall there are larger headway separations than in the base case, where bunching is very common.

Table 5-5: Standard deviation of average headway at stops

Route	Stop	Base Case	1.Headway deviation condition on all intersections	2.Headway deviation and load condition on all intersections	3.Headway deviation on all intersections and load condition on critical intersections	4.Headway deviation on non-critical intersections and no TSP on critical intersections
204	Pintor Cicarelli	1.97	1.78	1.27	1.84	1.73
204	Franklin	1.98	2.01	1.21	1.82	1.76
204	Nuble	1.98	2.01	1.99	1.82	1.68
204	Maule	1.98	2.03	2.00	1.82	1.64
204	Victoria	2.00	2.00	1.89	1.79	1.65
204	Santa Elvira	2.00	1.98	1.89	1.81	1.68
204	Matta	2.00	2.00	1.90	1.73	1.72
204	Copiapo	2.02	1.99	1.90	1.70	1.69
204	Av. 10 de Julio	1.94	2.03	1.81	1.70	1.55
204	Marin	1.88	1.90	1.69	1.62	2.00
204	Sara del Campo	2.42	1.70	1.46	1.27	1.76
204	Isabel Riquelme	1.98	1.77	1.26	1.89	1.62
204e	Pintor Cicarelli	9.95	12.42	18.80	9.75	9.45
204e	Victoria	15.85	12.71	18.52	9.79	9.78
204e	Matta	15.55	12.35	17.89	9.16	9.48
204e	Marin	15.17	11.57	20.42	9.05	8.85

The headway variability in Table 5-5 indicates that the standard deviation varies along the stops for each route, and that there is no specific behavioral pattern for each strategy. This can be expected since the calculation of the average headway was done considering only the previous arrival. Therefore, an analysis of the headways between all the vehicles is necessary to generate conclusions on the effects of TSP for this metric.

Tables 5-6 displays results for travel time and speed for general traffic, and are shown for a sample of different levels of traffic demand at intersections. Travel times and speeds for cross-streets are evaluated from the beginning of the previous intersection to the subsequent one, crossing the main corridor from the previous intersection to the following one.

Table 5-6: Vehicle travel time comparison with base case

	Base Case	1.Headway deviation condition on all intersections		2.Headway deviation and load condition on all intersections		3.Headway deviation on all intersections and load condition on critical intersections		4.Headway deviation on non-critical intersections and no TSP on critical intersections	
Intersection	travel time (min)	travel time (min)	% change	travel time (min)	% change	travel time (min)	% change	travel time (min)	% change
Marin	1.80	1.75	-2.66%	1.71	-5.14%	1.60	-11.08%	1.86	3.08%
Pintor Cicarelli	0.72	0.72	-0.84%	0.72	-1.01%	0.72	-0.95%	0.72	-0.70%
Franklin	0.78	0.78	-0.17%	0.77	-1.54%	0.79	1.38%	0.78	-0.37%
Santa Isabel	0.92	0.91	-1.58%	0.92	0.08%	0.90	-2.10%	0.93	1.16%
Matta E	0.92	0.92	0.07%	0.90	-1.43%	0.91	-1.05%	0.92	0.26%
Victoria	0.73	0.73	-0.21%	0.75	2.36%	0.73	0.22%	0.74	1.28%
Carmen	32.97	32.93	-0.12%	31.36	-4.88%	29.15	-11.59%	35.98	9.13%
10 julio	0.84	0.82	-1.98%	0.83	-1.22%	0.82	-1.96%	0.86	2.87%
Matta W	1.03	1.04	0.99%	1.03	-0.85%	1.03	-0.45%	1.05	1.20%

Table 5-7: Vehicle travel speed comparison with base case

	Base Case	1.Headway deviation condition on all intersections		2.Headway deviation and load condition on all intersections		3.Headway deviation on all intersections and load condition on critical intersections		4.Headway deviation on all intersections and no TSP on critical intersections	
Intersection	travel time (min)	travel time (min)	% change	travel time (min)	% change	travel time (min)	% change	travel time (min)	% change
Marin	7.91	8.26	4.46%	8.42	6.49%	8.84	11.73%	7.76	-1.94%
Pintor Cicarelli	25.32	25.43	0.40%	26.27	3.73%	25.57	0.96%	25.50	0.70%
Franklin	22.61	21.81	-3.52%	22.70	0.40%	22.33	-1.22%	22.69	0.36%
Santa Isabel	16.14	16.23	0.60%	14.67	-9.07%	16.46	2.04%	15.99	-0.89%
Matta E	17.61	17.61	0.01%	17.67	0.36%	17.78	0.99%	17.55	-0.35%
Victoria	19.66	19.74	0.43%	19.74	0.39%	19.62	-0.20%	19.41	-1.27%
Carmen	7.57	8.32	9.87%	7.33	-3.12%	8.54	12.81%	6.88	-9.15%
10 julio	19.65	20.10	2.28%	19.34	-1.55%	20.04	2.00%	19.14	-2.57%
Matta W	15.68	16.13	2.87%	15.83	0.96%	15.73	0.34%	15.46	-1.40%

Results of travel time and speed for general traffic do not seem to display specific behavior from which we could draw conclusions from. The reason for this may be that under these high congestion levels, where in some instances the controller receives several priority requests close together, general traffic appears to be very sensitive to interruptions in the phases. It seems that when the system operates near capacity, a small change or interference could result in larger disturbances in the area.

Table 5-8 shows the delays in total person hours and average delay per vehicle.

Table 5-8 Total delay and average delay

	Base Case		Headway deviation condition on all intersections		Headway deviation and load condition on all intersections		Headway deviation on all intersections and load condition on critical intersections		Headway deviation on all intersections and no TSP on critical intersections	
Marin	total delay (person-hrs)	avg delay (sec/veh)	total delay (person-hrs)	avg delay (sec/veh)	total delay (person-hrs)	avg delay (sec/veh)	total delay (person-hrs)	avg delay (sec/veh)	total delay (person-hrs)	avg delay (sec/veh)
10 Julio	39.13	48.37	40.71	52.65	37.59	39.36	32.77	37.04	38.25	50.38
P. Cicarelli	42.86	43.32	33.19	34.28	26.55	24.53	37.53	36.50	41.76	44.23
Franklin	41.94	39.94	41.91	40.38	41.98	39.44	43.02	40.84	42.71	41.50
Matta	57.44	65.49	54.83	63.68	51.32	58.58	62.75	73.13	57.56	67.74
Santa Isabel	130.51	53.39	132.92	55.74	101.72	40.50	130.51	52.00	131.02	54.72
Victoria	54.01	35.00	46.47	31.18	48.24	29.38	51.40	32.81	53.49	35.85

Results for total and average delays show a similar behavior to the travel time and speed results. Although the changes in average delay/vehicle do not exceed 12 seconds, when added up to total person-hrs for the complete period analyzed (3 hours), the difference is more marked because of the higher flows experienced in the corridor. Still, this data seems to imply that behaviors are particular in each replication, and no pattern can be drawn due to the high level of traffic demand.

5.6 Other bus priority strategies

Routes 204 and 204e have a bus lane through most of the corridor. However, the fact that the lane is shared with taxis, and that it is not properly enforced (and general traffic enters the lane to avoid congestion) limits the benefits an exclusive bus lane could bring. If a bus lane were to be fully implemented and enforced, improved reliability should be experienced due to the fact that buses will not be subjected to additional delays caused by congestion and interactions with other vehicles.

Signal coordination could also serve as a priority strategy if properly optimized and improved to favor buses, by considering average speeds between intersections, and dwell times on stops. This priority strategy should be a first option, since it incurs in little or no cost and could improve the efficiency of the system.

Chapter 6

Conclusions and Future Work

6.1 Summary

The primary objective of this research is to evaluate Transit Signal Priority strategies in the context of Bus Rapid Transit systems. The rationale for conducting this evaluation stems from the growing interest in BRT systems and the possible application of transit signal priority as a tool to increase ridership and improve operations. BRTs possess characteristics that distinguish them from conventional bus corridors and consequently they have to be analyzed separately. The challenge is that there is an urgent need to provide more transit capacity and better access in U.S. and in South American metropolitan areas as well as a need to increase the bus mode share by making them an attractive alternative, not only to private vehicles but also to rail transit.

Two corridors were evaluated using four different conditional signal priority strategies. The corridors evaluated were the Silver Line along Washington Street in

Boston and Route 204 and 204e along Carmen Avenue in Santiago, Chile. The priority strategies assessed, which consist of different combinations of headway and load constraints, are as follows:

- "Headway deviation condition at all intersections," where priority will be granted at all intersections to a bus that is running late, according to a comparison with the headway of the previous bus.
- "Headway deviation and passenger load condition at all intersections," where priority will be provided to buses that are running late, according to a comparison with the headway of the previous bus, and that also have a minimum number of passengers on board.
- "Headway deviation condition at all intersections and passenger load condition at critical intersections," where priority is granted to transit vehicles that are running late, according to a comparison with the headway of the previous bus along all intersections, except at critical intersections (cross-streets with v/c ratios higher than 0.7) where a passenger load condition is also applied.
- "Headway deviation condition at non-critical intersections and no TSP at critical intersections," where priority is provided to all transit vehicles that are running late, according to a comparison with the headway of the previous bus, except at critical intersections, where no priority will be provided.

The strategies were evaluated against a "Do nothing" scenario, using existing conditions in each corridor as the base case.

The effects of these strategies were analyzed under current conditions as well as for higher loads of traffic and transit demand to evaluate the sensitivity of the results to those important factors. Key performance metrics were presented for each strategy to assess the effect of TSP in terms of travel times, delays, and transit reliability.

6.2 Findings

The first case study of the Silver Line in Boston can be used to represent TSP effects under medium levels of traffic conditions, while the corridor in Santiago can be used to represent TSP effects under high congestion, with considerable interruptions generated by many transit vehicles operating close together. There are some general findings about the effects of TSP and some specific effects pertaining to individual corridor characteristics.

Overall, the results from both case studies support the belief that Transit Signal Priority can provide travel time reductions for transit vehicles as well as increases in average speeds, together with reductions in headway variability, which was also observed across scenarios. The first strategy, which uses conditional priority based on headway at all intersections, proves to be the one with the greatest benefit for the buses in terms of travel time, speed, and headway variability. The second strategy, which limits priority at all intersections based on headways and load constraints, displayed the least travel time and speed benefits for transit vehicles because often the load condition was not met at certain stops. The third strategy provides intermediate benefits between the first and second, since it applies a load condition only at critical intersections and is intended for reducing the negative impact on general traffic at cross-streets of those critical intersections. The fourth strategy, which provides no priority at critical intersections, provides the least overall benefits to transit vehicles as it tries to avoid impacting the high traffic levels that go through those intersections.

Similar results were observed in the base cases and scenarios with increases in traffic demand. Buses and through traffic experienced increased benefits in travel time and speeds, though the negative impact on cross-street traffic was higher under growth scenarios. Growth scenarios were highly sensitive to signal disruptions and queues were sometimes generated, particularly at cross streets with the highest demand levels (approaching the downtown area).

In the Silver Line 5 (SL5), the first strategy (only the headway constraint) proved to be the most beneficial for transit vehicles. The second (limited priority based on load) and fourth strategies (no alterations at the critical intersections) had impacted general traffic less. The 15% transit demand growth scenario showed greater benefits for transit vehicles in terms of travel time and speeds. The current condition case was similar but the growth scenarios provided even greater benefits. Headway variability improved in both current case and growth scenario, especially towards the last segment of the route where the bus lane comes to an end.

Although the Santiago case study showed similar results for transit travel times and speeds, the effects on average headways and general traffic was highly variable. In cases of high congestion where frequent priority requests are granted due to high frequencies, general traffic is very sensitive to interruptions that are the length of the cross-street phases.

Although further research is needed to make the models more robust and to test the sensitivity of the green extension and red truncation values based on a detailed study of the detector distance, this research provides insights on how transit signal priority will behave in situations of medium and high traffic demand levels as well as in high frequencies of up to 17 buses per hour.

6.3 Future Research

Further research is needed to more accurately predict bus behavior when conditional TSP strategies are applied using headway and load constraints. The software's inability to quantify the number of buses that benefit from priority signals at each intersection makes it difficult to do a complete evaluation of TSP effectiveness. To analyze a multi-route corridor, a separate analysis would be necessary to distinguish the effects on individual routes.

There is limited literature on the optimal distance for vehicle detection that will minimize negative effects on cross-street traffic while providing a reasonable time between the request and granting of priority. This could therefore be an important area of further research. More detailed analysis should also be conducted to evaluate the effects of different values of red truncation on cross-street traffic.

There are several other bus priority strategies that should be considered as possible alternatives to TSP. For example, signal coordination should be the first option to be evaluated since it has no additional infrastructure costs. This could be a good alternative in a segment like Kneeland and Temple Street where signal coordination could improve transit vehicle performance after the bus lane comes to an end.

A proper optimization should be performed to define the optimal coordination of traffic signals, broken down by segments. An analysis of transit travel speeds and dwell times between stops should be conducted to evaluate the possible benefits of passive priority. Different progression speeds should also be tested to optimize the effects on general traffic. This intervention will be most effective on segments with no bus lanes.

Another strategy that should be evaluated for BRTs is the implementation of full bus lanes for transit vehicles. Many incremental BRTs like the Silver Line and Carmen do not have exclusive bus lanes throughout the whole route. When they do, they sometimes share it with other vehicle classes. Further research should be performed to evaluate the full implementation of bus lanes, which will require a detailed analysis of the surrounding areas to account for possible increases in congestion caused by the dedicated lane that could shift traffic to other parallel but less congested routes.

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