Thesis Title: Signal Priority Near a Major Bus Terminal in Boston, Massachusetts.

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Signal Priority Near a Major Bus Terminal in Boston, Massachusetts

A Thesis Presented

by

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to

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Abstract

Giving priority to buses at traffic signals helps minimize person-delay and promotes use of public transportation. However, near major bus terminals, bus volume may be so high that it is impractical to interrupt the signal cycle for every bus requesting green. This study looks at priority strategies where bus traffic is high, and where buses are turning into and out of arterials with coordinated traffic signals. The objective is to minimize initial delay for buses, and then to dynamically provide them green waves through multiple intersections. Two challenges besides the very high bus volume are needed to maintain signal coordination for arterial non-bus traffic to prevent queue spillback, and resolving requests from conflicting streams of buses.

The study site is a network with four signalized intersections surrounding Ruggles Station in Boston. During the A.M. peak hour, 77 buses arrive and depart in mixed traffic on intersecting arterials that are near saturation. At the busiest intersection, only 3% of the vehicles are buses, yet 37% of the people passing through are bus passengers. Existing signal control has a coordination plan that favors through traffic, resulting in long delays to buses that have to turn into and out of the main arterials.

Numerous priority tactics are tested using a traffic microsimulation model (VISSIM), with signal control logic programmed using VISSIM’s internal language Vehicle Actuated Programming (VAP). They can be grouped into four general strategies:

- passive priority (an approach that does not rely on bus detection): adjusting cycle splits, phase sequence, and offsets to favor bus flows while still serving the main traffic flows
- active priority: green extension, early green, phase insertion, and phase rotation
• flexible control logic with natural compensation: cycle-constrained full actuation, coordination point floating, and dynamic coordination (where changes to the cycle at one intersection trigger corresponding changes at the next intersection in order to give buses a green signal at each intersection)

• capacity enhancement: modifications in signal timing plans to increase the capacity of intersections

Simulation results indicate that during the morning peak hour, by using multiple advanced priority strategies that combine aggressive priority with compensation to affected traffic streams, proposed improvements will halve average bus delay from 90 seconds to 44 seconds, for an average delay reduction of 22 seconds per bus per intersection with no detectable impact on non-transit traffic vehicle delay. Each of the priority strategies tested makes a substantial contribution to this overall improvement. The greatest benefit comes from passive priority, which creates a coordination pattern favoring transit that eliminates much of the need for buses to request priority. Substantial benefit is also gained from the active and advanced strategies tested except for dynamic phase rotation.
Acknowledgement

I am heartily thankful to my supervisor, Prof. Peter G. Furth, for his continuous guidance and support throughout my research, for his enthusiasm, and for the trust he has given me. Without his expertise, this thesis would not be truly complete and it has been my privilege to work with him.

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Thanks also for the assistance of Maaza Mekuria, who helped me with the technical aspects of this research.

Finally the most special thanks go to my family, who gave me their unconditional love and support throughout my life. Without their support, I would not be able to write these words. Thank you.
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Chapter 1: Introduction

Over the past decades, traffic congestion has become a major problem in big cities and metropolitan areas. It is responsible or directly related to social and economic costs by decreasing mobility, increasing fuel consumption as well as air pollution, and imposing stress on road users. Even though congestion affects all transportation users, the impact on public transit is more significant. Congestion not only increases in-vehicle travel time, but also passenger waiting time at transit stops by increasing transit travel time variability and decreasing transit reliability. Moreover, most of the transit routes are fixed, not allowing transit drivers to use less-congested routes when they get stuck in traffic. As a result, traffic congestion decreases the attractiveness of transit, thereby increasing the relative attractiveness of other modes which may make traffic congestion more severe. To break this cycle (congestion – less transit use – more congestion), congestion protection for transit is critical for transit efficiency. One of the most effective strategies to reduce the impact of congestion on transit vehicles is transit signal priority (TSP) [1].

TSP has been used both in Europe and the United States for several years as a preferential treatment to improve operation of transit vehicles. It reduces transit travel time and delay and improves reliability, thereby reducing waiting time of passengers, reducing unnecessary fleet size, and increasing ridership [1].

Conversely, one of the main concerns of TSP is its potential adverse impact on all other traffic (i.e., non-priority), especially at intersections operating at or near saturation. One TSP caveat is over-estimating the benefits. Models historically overestimate negative impacts on private automobiles, ignoring the fact that automobile drivers can
find another route to reduce their delay, and to underestimate positive impacts on transit by not considering the increase in transit ridership resulting from faster and more reliable transit service.

### 1.1 Transit Signal Priority Tactics

TSP implementation can be accomplished in several different ways, including passive priority, active priority, and adaptive priority, which are discussed as follows:

Passive priority does not depend on transit detection/priority request generation system and it operates continuously. Passive priority is generally used when transit operations are predictable with a good understanding of transit route and passenger loads.

As opposed to passive priority, active priority tactics require detection or priority request activation to grant priority to transit vehicles. The two most popular active priority tactics used both in the United States and Europe are green extension and early green. Other active tactics, which are less frequently used, are phase insertion and phase rotation.

Green extension is the extension of green time beyond the specified maximum green when an approaching transit vehicle is detected.

Early green tactic shortens the green time of preceding phases (non-transit phases) when a transit vehicle is detected in order to speed up the return to green for the transit phase.

Phase insertion is the insertion of a special phase when a transit vehicle is detected and requests priority for this phase.
Phase rotation is the rotation in the signal timing plan when a transit vehicle is projected to arrive at an intersection during red phase. The main goal of phase rotation is to reduce the red time of transit vehicles and to reduce transit delay.

Active priority tactics can be categorized as absolute priority and conditional priority. While absolute priority means that priority is given to every transit vehicles regardless of being late or early, conditional priority means priority is given to transit vehicles only if they are behind schedule.

Adaptive priority considers the trade-offs between traffic and transit delay. Real time information for both transit (e.g., current position of transit vehicle and its predicted arrival time at intersection) and traffic (e.g., number of cars in the queue, signal status at the upstream and downstream intersection) is used to accommodate TSP with minimum impact on overall traffic.

**1.2 Problem Statement**

Providing TSP at signalized intersections near a major bus terminal is a particular challenge due to the high frequency of priority requests. Conventional active TSP strategies that give extra green time or less red time to only one particular bus route coming from a specific direction may be simple enough on a street with infrequent bus service. However, near a major bus terminal, bus volume may be too high to interrupt the signal plan for every bus, and buses coming from different approaches often create simultaneous competing priority requests. Furthermore, bus movements near a bus terminal are the minor turning movements since the terminals are typically located alongside arterials and collectors, where the coordination plans along arterials favor through traffic, not buses turning into or out of the terminal. This is very different from the
common situation of TSP for a bus route operating along a major arterial, in which the main coordinated movements often benefit from TSP.

This research examines a particular site, comprising four signalized intersections around Ruggles Bus Terminal in Boston, during the A.M. peak hour. The goal is to reduce bus delay as much as possible through application of TSP without disrupting the general flow of overall traffic. This research involves both the application of traditional priority strategies and development of new strategies.

1.3 Research Objectives

The primary objective of this research is to provide priority tactics for buses near a major bus terminal, while minimizing person delay without imposing any substantial impact on the overall traffic. Coordination plans favoring buses that turn into or out of the terminal, while maintaining signal coordination for the through traffic along the arterials to prevent queue spillback and gridlock, where traffic queues block upstream intersection and causes traffic jam in which no vehicular movement is possible, play a vital role in reducing bus signal delays and minimizing the interruption of signal timing plan around a major bus station. In cases where desirable coordination plans for buses can not be attained, application of active priority tactics and a more sophisticated approach, namely dynamic coordination through multiple intersections will be considered.

Bus signal priority near a terminal has been a well-known concept for several years; however it has been rarely implemented due to its complications and transit and traffic agencies’ concerns [2]. Some of the problems addressed by transit agencies are:

- Impact on cross street or in general non-priority traffic
- Impact on competing bus routes
• Pedestrian constraints
• Hardware/software constraints
• Driver expectancy

Throughout this research, those concerns have been addressed and it has been found that a huge benefit (average bus delay reduction of 46 seconds) for buses can be achieved with minimum impact on general traffic through the usage of multiple and intelligent priority tactics.

1.4 Research Approach

A microsimulation model was developed in this thesis to test different priority scenarios around the terminal. Data collection was performed from the field and the model was calibrated and validated to mimic the existing traffic conditions. Priority tactics were developed and applied in the simulation context to determine their effectiveness.

1.5 Overview of Ruggles Bus Terminal

Ruggles Station is a Massachusetts Bay Transportation Authority (MBTA) subway station on the Orange Line and a Commuter Rail Station serving the Providence/Stoughton, Franklin, and Needham lines. It also includes a major bus terminal in Boston used by 13 different bus routes, with 96 buses leaving and entering during morning peak. (Figure 1-1).
A private bus service is also provided between Ruggles Station and Longwood Medical Area (LMA), an area with a high density of internationally renowned hospitals, colleges, and biomedical research centers including Harvard Medical School. Ruggles station is also a major destination in itself, being within walking of Northeastern University (distance < 0.25 miles) and several colleges.

1.6 Thesis Organization

This thesis is organized in six chapters. Chapter 2 reviews applications of transit signal priority in United States and the literature that is most relevant to the research objectives.

Chapter 3 starts with a description of the case study and the implementation of the network in the microsimulation model, and then evaluates the existing signal timing plan.
In Chapter 4, general priority tactics to improve operation of buses around a major bus terminal and their applications in our case study are presented.

Chapter 5 includes the evaluation of applied priority tactics based on the microsimulation results.

Chapter 6 concludes with a summary of findings, general conclusions about TSP near major bus terminals, and suggestions for future research.
Chapter 2: Literature Review

Transit priority at signalized intersections has been studied in the United States since the 1970s [4] and applications started even earlier in some parts of Europe. While numerous studies have been reported over the years to assess the benefits and impacts of TSP, none of them specifically include priority strategies around a bus terminal.

This chapter reviews previous research on transit signal priority. Section 2.1 emphasizes recent applications of signal priority in the U.S. and Canada, and Section 2.2 focuses on some of the research papers on priority.

2.1 Applications of TSP in the U.S. and Canada

According to the Transit Signal Priority Handbook, a survey conducted in 2004 revealed that 24 agencies in the U.S. and Canada have operational TSP systems. Table 2-1 lists the agencies/cities having TSP and the year of TSP implementation.
Table 2-1 Transit Signal Priority Implementation in the United States and Canada, By Year [1]

The majority of the TSP applications were completed in the late 1990s (Table 2-1). The agencies indicated that approximately two-thirds of TSP tactics are only for bus applications when buses mostly operate in mixed traffic, and the remaining one third is for both bus and light rail transit (LRT). The magnitude of TSP applications varies throughout the U.S. from two intersections to more than 1500 intersections (Table 2-2).
<table>
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<th>CITY</th>
<th>ST</th>
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Table 2-2 Signalized Intersections with Transit Signal Priority in the United States and Canada [1]

According to Transit Signal Priority Handbook, the most common strategies for buses operating in mixed traffic were green extension and early green. Additional strategies including predictive priority and phase skipping were also utilized by several agencies. While some of the transit agencies applied absolute priority, many deployed conditional priority. Table 2-3 displays different TSP strategies used by agencies.
<table>
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<tr>
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<td>Tacoma</td>
<td>WA</td>
<td>EG, GE, O</td>
</tr>
<tr>
<td>Port Authority of Allegheny County</td>
<td>Pittsburgh</td>
<td>PA</td>
<td>PI</td>
</tr>
<tr>
<td>Sacramento Regional Transit District</td>
<td>Sacramento</td>
<td>CA</td>
<td>EG, GE</td>
</tr>
<tr>
<td>Santa Clara Valley Transp. Authority (VTA)</td>
<td>San Mateo County</td>
<td>CA</td>
<td>EG, GE, PI, O</td>
</tr>
<tr>
<td>Skagit Transit</td>
<td>Burlington</td>
<td>WA</td>
<td>EG, GE</td>
</tr>
<tr>
<td>Southeastern Pennsylvania Transp. Authority</td>
<td>Philadelphia</td>
<td>PA</td>
<td>EG, O</td>
</tr>
<tr>
<td>St. Cloud Metropolitan Transit Commission</td>
<td>St. Cloud</td>
<td>MN</td>
<td>EG, GE</td>
</tr>
<tr>
<td>Tri-County Metropolitan Transit District (TriMet)</td>
<td>Portland</td>
<td>OR</td>
<td>EG, GE, O</td>
</tr>
<tr>
<td>Utah Transit Authority (UTA)</td>
<td>Salt Lake City</td>
<td>UT</td>
<td>EG, GE</td>
</tr>
<tr>
<td>Washington Metro. Transit Authority (WMATA)</td>
<td>Washington</td>
<td>DC</td>
<td>EG, GE</td>
</tr>
</tbody>
</table>

EG = Early Green (red truncation)    GE = Green Extension
PI = Phase Insertion            PR = Preemption            O = Other

Table 2-3 Transit Signal Priority Strategy by Agency in the United States and Canada [1]

Finally eight case studies were conducted by the transit agencies in the U.S. and Canada. Four of these studies, which demonstrate good and bad examples of TSP implementation in the U.S., will be discussed in the following pages to explore transit agencies’ experiences and to evaluate the efficiency of TSP applications.
• **Los Angeles, County Metropolitan Transportation Authority (Metro)**

Los Angeles has 200 Metro Bus lines and five Metro Rail lines [5]. Metro provides bus rapid transit (BRT) as well, with less frequent stops, headway based schedules, frequent service, and TSP.

BRT was implemented on nine corridors and TSP is provided at 654 intersections. Conditional priority based on headway management is applied. Priority is only granted to buses whose headway is equal to or greater than the scheduled headway. Early green, green extension and phase hold are used as priority tactics which is provided only for metro rapid buses, not for local bus routes in the corridor.

The analysis showed that bus travel time reduced was by 19% to 25%, with priority accounting for about 1/3 of the gain and the rest due to having fewer stops. TSP typically caused 1 second of extra delay per auto per cycle for the side street.

• **TriMet, Portland, OR**

TriMet provides public transportation in the Portland, Oregon, metropolitan area. TriMet has a total of 660 buses grouped into 18 fleets that represents different sizes, makes, and models of a vehicle. As many as 645 buses may be in service during weekday peak hours [6].

The Portland case study includes eight corridors and 370 intersections. Conditional priority is implemented based on the following criteria: 1) Door is closed (if priority is requested at intersections having near-side bus stops) 2) On route, 3) 30 seconds or more late. The system is integrated with automatic vehicle location (AVL) system to check the current location of buses. Data were collected after the implementation to update bus schedules incrementally, creating fine-tuned schedules in
order to make conditional priority effective. Green extension and early green are used to provide signal priority. The system does not give priority to a bus request in the cycle following a cycle in which priority was requested.

These strategies reduced the variability in running time, thereby reducing recovery time (time added to the schedule to compensate for running time variability), and increasing reliability. They estimate that buses experienced a 10% improvement in travel time and 19% improvement in travel time reliability [1].

- **Pace, Chicago, IL – CERMAK ROAD CORRIDOR**

  Pace is the suburban bus division of the Regional Transportation Authority in the Chicago metropolitan area, with buses having generally longer headways (between 20 minutes to 60 minutes) than Chicago Transit Authority (CTA) buses [7].

  Fifteen intersections on 2.5 mile corridor were equipped with TSP to give priority to Pace buses. Priority is requested by all buses regardless of being late or early, and green extension and early green tactics are implemented as priority types.

  In this 2.5 miles of corridor, full optimization of traffic signals and activation of priority reduced the running time of East Bound (EB) & West Bound (WB) buses by 15% (3 minutes), amounting to 12 seconds per intersection. Actual running time reductions varied from 7% to 20% depending on the time of the day. Field studies indicated that there is little impact on non-priority street traffic [1].
• MBTA, Boston, MA

TSP is not widely applied in the Boston Metropolitan Area. According to a study conducted by ITS in 2006, less than 1% of the intersections in Boston are equipped with TSP.

The Silver Line on Washington Street is a new service, operating mostly in a combined bus and right-turn only lane, with some sections operating in mixed traffic and a short segment of an exclusive contraflow lane. Priority is provided at the four major signalized intersections with far-side bus stops [8]. The priority logic for the Silver Line is to request priority only for vehicles that are behind the schedule. In addition to that, priority is granted only if the priority has not been given on the previous cycle and if the occupancy on the side street is less than 40%.

No quantitative studies based on the field data have been conducted yet along the corridor to evaluate the impact of TSP on Silver Line. However a simulation model was developed in 2005 and it was found that TSP made almost no difference in running times [9]. For the morning peak, average inbound and outbound running times decreased by 10 seconds. For afternoon peak, average inbound running time decreased by 15 seconds, but average outbound running time increased by 30 seconds.

The reasons behind ineffective TSP for Silver Line are worth discussing and can be explained as follows:

• At intersections with little cross-traffic, bus delay was already very low and therefore TSP could not provide much benefit for transit [9].

• At intersections with a lot of cross traffic, priority was inhibited by the occupancy condition [9].
2.2 Research Papers on Priority

A study was conducted to evaluate the potential benefits of implementing transit signal priority along Columbia Pike, a fixed-time signalized arterial, in Arlington, Va [10]. A microscopic traffic simulation model was used to evaluate the effect of a number of alternative priority strategies on both buses and general traffic during the morning peak and midday traffic periods. Evaluations were conducted during both the morning peak period with relatively high and directional traffic flows, and the midday period when there is less traffic demand. Green extension and early green recalls were used in this study within a fixed-time, coordinated environment. Three different scenarios were analyzed. First, the priority logic was applied to only express buses, then regular and express buses, and finally all buses in the system.

Simulation results indicated that travel time for express buses was reduced by 2.3% to 2.5% during morning peak when priority was provided exclusively to them or in conjunction with other buses running along the arterial. Regular bus service also experienced reduction in travel time (-4.8%) when priority was granted to them, however the reduction in delay amounts to only one second per bus per intersection. For the general traffic, application of transit priority for all buses resulted in an 18% increase in average travel time and 14% increase in average delay. Much smaller negative impacts were obtained when priority was given exclusively to express buses, because there are only 10 express buses per hour as compared with 61 regular buses. Intersection specific analysis revealed that after the implementation of transit priority, average cross-street delay remained less than 10s/veh in most of the approaches and did not exceed 19s/veh. At only two intersections, dramatic delays were observed (on average delay varied...
between 45s to 160s per vehicle) where this large delay was mostly attributed to the fact that those two intersections carry significant amount of cross-street traffic, and any reduction in green time creates congestion and long queues.

A study aimed at developing more aggressive and innovative priority tactics was performed on Avenida Ponce de Leon in San Juan, Puerto Rico. Along the arterial, up to 36 buses operate per hour in mixed traffic northbound and in an exclusive contraflow lane southbound [11]. The section studied had 16 signalized intersections operating under fixed time control with a 90-s cycle, and 16 bus stops. Both conditional priority and absolute priority were tested. Priority tactics included green extension, early green and early red. Early red was used in a non-conventional way to reduce capacity loss at the intersections. In San Juan, there are no bus pull-offs and buses stop in the travel lane. To reduce capacity loss, the street that the bus is traveling on is forced to an early red when a bus is boarding/alighting passengers at a near-side stop by truncating the bus street’s green. Once the door is closed and the bus is ready to move, the signal returns to green as soon as possible. In addition to these strategies, full actuation was used at the intersections to get benefit of actuation when the traffic flow is not so heavy, with peer-to-peer communication between signals providing dynamic coordination.

A microsimulation study showed that compared with the existing condition, actuated control strategy with conditional priority decreased the transit delay by 13 person-hours per hour, and reduced delay to all travelers 36.6 person-hours per hour. Moreover, the applied strategies diminished average transit delay by 7.5 seconds per bus per intersection. They also pointed out that the average cycle length was decreased from
90 s to 52.8 s by implementing actuated control which may explain most the reduction in delay.

The San Juan study demonstrated that signal priority can reduce bus signal delay considerably without any substantial impact on general traffic even in a case in which bus frequencies are high. The key to its success was applying a highly interruptible signal control logic that responds quickly to, and recovers quickly from priority interruptions. Important features of “highly interruptible” control are:

- Unlike traditional green extension and early green, it uses tactics that compensate interrupted cross streets. The compensation tactics include full actuation (naturally keeps a light green for a longer time if a queue becomes longer) and early red.

- Because cross streets are compensated, priority can be aggressive, without limitations on granting priority in successive cycles.

- It uses dynamic coordination, with each green start calling for green at the next intersection, instead of coordination based on a fixed cycle. That way, there is no need for any intersection to return to coordination after a priority interruption.

This great degree of flexibility was made easier to apply because the arterial has one-way traffic as well as bus contraflow.

Ekelia, Sayed, and Esawey developed a Dynamic Transit Signal Priority (DTSP) strategy to overcome the static nature of conventional TSP and to take into account real-time traffic and transit conditions [12]. Two case studies were performed. In the first one, a hypothetical intersection was simulated, while second case study simulated a proposed LRT line, called the Evergreen line. Unlike conventional TSP systems where fixed
check-in and check-out detectors are used (loop detectors to detect buses with fixed location), an AVL system was used (in the microsimulation model) for the dynamic detection of transit vehicles. A linear model was used for arrival time prediction, and seven different response tactics were developed based on the predicted arrival time. Three TSP solutions were used; green extension, early green, and cycle extension. In the cycle extension strategy, the cycle was extended to one and half times the normal cycle to ensure that the transit vehicle will arrive on green. Signal coordination is retained by adjusting subsequent cycle lengths.

The proposed LRT line (Evergreen Line) has its own right of way, with 3 minute headways and at-grade crossings at 17 signalized intersections. Simulation results showed that the dynamic TSP strategy reduced LRT travel times by 1.6 minutes in the EB direction and by 1.4 minutes in the WB direction, corresponding to 5.3 seconds reduction per LRT vehicle per intersection. Furthermore, the travel timing savings with dynamic TSP were greater than the classic TSP and the travel time reductions were more evident at intersections with higher traffic. Finally, for the impact on the cross streets, dynamic TSP showed lower or at least equal delays compared to the no TSP approach at 13 intersections out of 17.

Furth and Muller conducted conditional bus priority research about at signalized intersections on a bus line in Eindhoven, Netherlands not only as a means of improving speed and reducing delay, but also for service reliability and schedule adherence [13]. Vehicles that are ahead of schedule are denied priority, while late buses are pushed ahead to keep the buses on schedule.
With conditional priority, buses were rarely more than 60 s early or more than 120 s late and throughout the line, and the distribution of schedule deviation remains tight (having small standard deviation), whereas with no priority the schedule deviation is much larger. A field test conducted at the busiest intersection found that when buses were given absolute priority, delay to general traffic increased by 40 s per vehicle, whereas the general traffic delays with conditional priority was almost the same as when no priority was applied. The traffic capacity loss with absolute priority approached 20 percent, while the impact of conditional priority is much smaller, only about 5 percent loss of capacity. Finally when there is no priority, buses were delayed an average of 27 s, falling to 3 s when buses have absolute priority, a saving of 24 seconds per bus at this intersection. With conditional priority, early buses get no delay reduction, but this is a positive outcome. Late buses saw their delay reduced, as in the absolute priority case, from 27 to 3 seconds.

The priority logic in Eindhoven study is very aggressive, truncating competing streams to their minimum green; and using advanced detection to turn the signal green before the bus arrives, flushing out the queue ahead of it. However, because there is little means of compensating competing traffic streams, the approach used there is not scalable. With conditional priority, there is about one interruption every 10 minutes; but under absolute priority, the frequency of interruptions become once every 5 minutes, and the capacity loss to the cross street became severe.

The United States applications and research papers indicate that the mechanisms behind TSP should be well understood in order to provide a real priority that offers benefits for transit vehicles with minimum impacts on general traffic. Therefore,
designing highly interruptible traffic signal controls with multiple and intelligent priority strategies is one of the key steps in the process of implementing signal priority. Using more aggressive tactics with compensation and continuous improvements based on field studies is essential to improve the performance of TSP.
Chapter 3: Base Scenario

3.1 Introduction

The case study presented in this chapter explains the development of the traffic simulation model and critiques the existing signal timing plan.

Assessment of the existing signal timing plans was obtained by field observations and microsimulation analysis. Data collection was conducted in the field and a microsimulation model was developed using VISSIM to model existing conditions and to evaluate future alternatives. Finally, model calibration and validation conditions were performed using field data to ensure that model reflects actual or real world conditions.

3.2 Data Collection

The data used throughout this study were gathered from a number of sources (Table 3-1).

<table>
<thead>
<tr>
<th>Data</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus Routes and Schedules</td>
<td><a href="http://www.mbta.com">http://www.mbta.com</a></td>
</tr>
<tr>
<td>Existing Signal Timing Plans</td>
<td>Boston Transportation Department (Signal Timing Plans) and Field Studies, 2008 (Validation of Signal Timing Plans and Modifications If Needed)</td>
</tr>
<tr>
<td>Traffic Volumes</td>
<td>Institutional Master Plan Amendment for Northeastern University Campus, prepared by Vanesse Hangen Brustlin (VHB), Inc., Oct 2006 [14] and Field Studies, 2008 (Validation of Traffic Volumes and Modifications If Needed)</td>
</tr>
<tr>
<td>Intersection Layout and Geometry</td>
<td>Field Studies and Google Earth</td>
</tr>
</tbody>
</table>

Table 3-1 Source of Collected Data to Implement Network in VISSIM
The modeled network includes seven intersections around Ruggles Bus Terminal where bus signal priority was tested at four intersections (Intersection #2-3-5-6). Figure 3-1 displays the layout of the intersections and the crosswalks which have protected green phase in the signal timing plan (i.e., pedestrians have a separate green light and they do not walk concurrently with the traffic) around Ruggles Bus Terminal.

Figure 3-1 Project Area and Ruggles Bus Terminal (Not to scale)

The terminal has two entrances and one exit. Buses coming from the West and North use the main entrance, while buses coming from East and South use the back entrance. All outgoing bus routes use the busway exit. All these intersections except Intersection #6 are actuated and coordinated, having a cycle length of 100 seconds in the A.M. peak. Intersection #6 has fixed time control with a cycle length of 90 seconds.
Figure 3-2 shows A.M. peak traffic volumes (including buses) at the four intersections at which priority was tested. Since the traffic volume data provided by a consulting firm was collected in 2006 (Table 3-1), field studies were conducted in order to verify the traffic volumes. Field studies indicated that except Melnea Cass-Columbus intersection (intersection #6), there has not been any significant change in traffic volume for the last three years (2006 – 2008). Thus, only the volumes at intersection #6 were adjusted, and the rest of the VHB counts were used as it is (Figure 3-2).

Figure 3-2 indicates that the busiest intersection is intersection #3 with the highest vehicle volume as well as a very high bus volume (131 buses/hour).
The numbers within parentheses display bus flows during A.M. peak, while the numbers without parentheses display total volume including buses. At the busiest intersection (Intersection #3), assuming average car occupancy of 1.15 and average bus occupancy of 20, buses account for 3% of vehicles whereas people on bus account for 37% of travelers.

In total, 13 different bus routes use the terminal, with 96 buses entering and exiting (Tables 3.2 and 3.3). All buses use the busway exit at intersection #2 to leave the terminal. The 20 buses per hour exiting towards the north (right-turning buses) can turn right on red, effectively leaving the system with little delay.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Route Number</th>
<th>Frequency(bus/hr)</th>
<th>Total Buses per Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>From Ruggles Station to West Tremont Street</td>
<td>23</td>
<td>12</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>44</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>From Ruggles Station to East Tremont, South Ruggles and South Melnea Cass</td>
<td>CT3</td>
<td>4</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>8 Outbound</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>19 Outbound</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>47 Inbound</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>From Ruggles Station to North Ruggles Street</td>
<td>CT2</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>CT3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8 Inbound</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>19 Inbound</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>47 Outbound</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-2 Outgoing Massachusetts Bay of Transportation Authority Bus Volumes from Ruggles Terminal, Boston MA
Note that routes 8, 19, 47 and CT3 use Ruggles Terminal as an intermediate stop, whereas the terminal is a destination for other routes.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Route Number</th>
<th>Frequency(bus/hr)</th>
<th>Total Buses per Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Tremont Street to Ruggles Station (Main Entrance)</td>
<td>15</td>
<td>11</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>44</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>South Melnea Cass to Ruggles Station (Back Entrance)</td>
<td>8 Inbound</td>
<td>4</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>47 Outbound</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>19 Inbound</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CT3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>North Ruggles Street to Ruggles Station (Main Entrance)</td>
<td>8 Outbound</td>
<td>4</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>47 Inbound</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>19 Outbound</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CT2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CT3</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-3 Incoming Massachusetts Bay of Transportation Authority Bus Volumes to Ruggles Terminal, Boston MA

In addition to the MBTA buses, there are also private shuttles (e.g., LMA) on north side of the terminal; however these buses are not affected by the roads or signals in the case study and have not been included.

3.3 Network Implementation in VISSIM

VISSIM is microscopic traffic flow simulation software developed by Planung Transport Verkehr (PTV) AG in Karlsruhe, Germany [15]. The use of microsimulation
models in traffic engineering projects, which has the ability to simulate the behavior of individual vehicles on the network, has been increasing drastically and has becoming one of the most popular tools for transportation engineers to conduct traffic studies, analyses and evaluations [16].

Microsimulation models are much faster, less expensive and more flexible than field implementation. Moreover when compared to conventional analysis techniques (e.g., Highway Capacity Manual, HCM), they are more effective and can be more accurate, because they typically allow simulating traffic systems on a vehicle-by-vehicle basis by updating position, speed, acceleration, and other state variables on time steps, such as on a second or tenths of a second basis.

The key features of VISSIM that make it one of the most appealing traffic simulation models can be listed as follows:

- VISSIM is a multi-modal microscopic simulation program that allows modeling pedestrians, bicycles, cars and light rail.
- VISSIM is a very effective simulation program in simulating transit behavior. It is able to model transit routes, various transit vehicle types, schedules, stops as well as dwell times of passengers.
- VISSIM allows changing the driver behavior parameters (e.g., reaction time, average standstill distance) to model traffic accurately.
- Signal control logic is very flexible, making it possible to model fixed, actuated and adaptive signal controllers with TSP or vehicle preemption.

The major steps followed in this study to implement network and to overcome experienced shortcomings in VISSIM is provided as follows.
VISSIM allows using any picture as a background image for model’s network [17]. The model layout was based on a map from Google Earth, and appropriately scaled.

The volume of traffic to be simulated in the network was specified as origin-destination (O-D) matrices. The traffic flow was modeled using O-D flows, which contains the number of trips for every pair of planning zones for a given time interval.

In the model, Dynamic Assignment was used rather than Static Routing Decision, which allows to model networks without static routes. In other words, vehicles do not follow routes through the network that were manually defined by the user, but instead routing assignment is done dynamically based on the generalized cost they have experienced during the preceding simulations. Generalized cost is computed based on travel time, combination of distance and other costs (e.g., tolls). Distance and costs are defined directly within the network model but travel time is a result of the simulation. Therefore, VISSIM measures travel times on all edges in the network during one simulation so that the route choice decision model in the next simulation can use these values. In this study only travel time was considered as generalized cost component because of the models’ limited size. Therefore, drivers may change their routes dynamically based on travel time during the preceding simulations instead of following a predefined static route according to the existing traffic conditions.

In VISSIM, while non-transit vehicles are generated according to Poisson process, which introduces variability in the model, there exists no randomness in transit vehicle generation. Transit vehicles follow exactly the same schedule in the simulation program provided by the user. However in reality, there is always variation in the scheduled running time and the deviation is stronger for incoming buses. In order to model this
random arrival process for buses, a dummy bus stop was created at the beginning of each transit route for both incoming and outgoing buses. Since the cycle length for intersections is 100 seconds for all but one of the intersections, a uniform distribution with minimum 0 seconds and maximum 100 seconds was selected for the dwell time distribution to account for randomness so that buses arrive at the intersections at any time in a cycle.

For signal controllers, VISSIM’s optional add-on module, vehicle actuated programming (VAP), was used to test recommended strategies since VAP is much more flexible, and hence more effective in modeling TSP than conventional controllers (e.g., fixed time control, NEMA control). VAP allows users to program their own signal control logic including special features (e.g., transit priority, emergency vehicle preemption) [18]. VISSIM is also compatible with the traffic controllers, and can interface to traffic signal controllers type NEMA, 170, 2070, and Siemens.

3.3.1 Calibration and Validation

Using the simulation model with default parameters may not reflect the site conditions. Especially under congested conditions, achieving accurate results requires proper calibration and validation. Unfortunately, traffic engineers and analysts often ignore these two important steps. Therefore it should be noted that even though simulation models are effective tools in testing and evaluating different scenarios, they can produce unreliable results unless appropriate adjustments are made.
3.3.1.1 Calibration of Microsimulation Models

Calibration is a process of adjusting or tuning the parameters to reflect the observed conditions in the study area. VISSIM and other microsimulation models allow users to change the default parameters (e.g., minimum acceleration rate, average standstill distance, and parameters related to lane changing behavior).

Researchers and practitioners have used various parameters to calibrate traffic simulation models, and some of the field key parameters that have the greatest impact on the model performance are as follows [19] [20]:

- Discharge Rate/Headway (Reciprocal of the Saturation Flow)
- Queue Length
- Travel Time Data
- Average Travel Speed
- Density

3.3.1.2 Model Calibration

In this study for initial calibration, discharge headway for the East Bound Left (EBL) approach at the intersection of Tremont – Ruggles (Intersection #3) was analyzed, because this is a critical approach that experiences temporary oversaturation during A.M. peak. Using the default parameters, the simulated queue for this approach was too long (unrealistic) and did not reflect the observed field conditions. For the first step of calibration, car following model parameters were changed in VISSIM since these parameters have the greatest effect on discharge headway.

The following formulas describe the car following model parameters and their relationship with discharge headway.
According to Wiedemann 74 Car Following Model [17],

\[ d = ax + bx \]

where \( d \) is the distance between two vehicles

- \( ax \) is the standstill distance
- \( bx \) = \((bx\_add + bx\_mult*z)\)*√\(v\)

- \( bx\_add \) = additive part of desired safety distance
- \( bx\_mult \) = multiplicative part of desired safety distance
- \( v \) is vehicle speed
- \( z \) is a value of range \([0, 1]\) which is normal distributed around 0.5 with a standard deviation of 0.15.

Based on the relationship, an increase in \( d \) results in an increase in discharge headway (or decrease in saturation flow rate). The default simulation parameters and the adjusted values are summarized in Table 3-4.

<table>
<thead>
<tr>
<th></th>
<th>Default</th>
<th>1\textsuperscript{st} trial</th>
<th>2\textsuperscript{nd} trial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Standstill Distance (ft)</td>
<td>6.56</td>
<td>6.23</td>
<td>5.58</td>
</tr>
<tr>
<td>Additive Part of Safety Distance</td>
<td>2.00</td>
<td>1.50</td>
<td>1.10</td>
</tr>
<tr>
<td>Multiplicative Part of Safety Distance</td>
<td>3.00</td>
<td>2.60</td>
<td>2.50</td>
</tr>
<tr>
<td>Desired Acceleration (Only for Buses)</td>
<td>Max=4.9 ft/s(^2) for 0&lt;v&lt;13mph</td>
<td>Max=4.9 ft/s(^2) for 0&lt;v&lt;13mph</td>
<td>Max=5.5 ft/s(^2) for 0&lt;v&lt;13mph</td>
</tr>
</tbody>
</table>

Table 3-4 Adjustment of Car Following Parameters to Match Simulation Data to Field Data

After the parameters were adjusted, the results of VISSIM and field data were compared for the average discharge headway (Table 3-5).
<table>
<thead>
<tr>
<th></th>
<th>Field Data</th>
<th>Default (VISSIM)</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; trial</th>
<th>2&lt;sup&gt;nd&lt;/sup&gt; trial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge Headway (s/veh)</td>
<td>2.287</td>
<td>2.414</td>
<td>2.362</td>
<td>2.265</td>
</tr>
<tr>
<td>Saturation Flow Rate (veh/hr)</td>
<td>1574.1</td>
<td>1491.3</td>
<td>1524.1</td>
<td>1589.4</td>
</tr>
</tbody>
</table>

**Table 3-5 Comparison of Field and Microsimulation Model for Calibration of East Bound Left Approach at Ruggles-Tremont-Whittier Intersection**

Based on the model calibration, a slight deviation still exists between the simulation output and the observed results. This can be expected due to the complexity of the program and real life. The stochastic nature of the simulation programs couple with the variation in the actual traffic contribute to the variation. Moreover, since no anomalous vehicle movements were observed during the visual validation step after the calibration, it was decided to proceed with validation.

**3.3.1.3 Model Validation**

Validation is the process of testing the simulation model with the calibrated parameters. Validation must not be performed with the data used for calibration; a different set of data are required. If the results match the field observations, then it can be concluded that the simulation model reflects the real conditions, and other data can be analyzed. Alternatively, if there is a discrepancy between the results and real world observations then the parameters should be recalibrated.

For validation, the focus was on the average travel time of MBTA Buses for a specific section. Field collected data included a one hour period during the A.M. peak (7:30 - 8:30 A.M.) during which 53 buses arrived. Figure 3-3 displays travel time distribution for 53 buses based on conducted field study.
The average travel time section includes two signalized intersection (Intersection #2 and Intersection #3) and no bus stops. Two end points were used to identify the travel time. The origin was specified as the stop line on Tremont Street at the intersection of Tremont and Prentiss (Intersection #7) and the destination was specified as the main entrance of Ruggles Bus Terminal. The traffic volume for that particular day was also counted and compared with the simulation input volume to be able to make consistent comparisons. The field data indicated that the EBL traffic volume for that particular day was 250 vehicles/hour, being very close to the simulated data (260 vehicles/hour).

Figure 3-4 illustrates the average travel time for MBTA buses based on the microsimulation model.
Figure 3-4 Massachusetts Bay of Transportation Authority Buses’ Travel Time Distributions Based on Field Observation and Simulation Model

Maximum average travel time observed in the field is approximately 350 seconds whereas it is around 450 seconds according to calibrated simulation model and might even reach to 530 seconds in extreme cases. Moreover, there is about 40 seconds difference in average travel time when comparing the field data to the simulation model. This is a significant amount of difference considering the length of travel section (about 0.3 miles) Therefore, it was concluded that the simulation model has to be recalibrated.

Field observations revealed that although the green duration for EBL approach at the intersection of Tremont and Ruggles (Intersection #3) is 16 seconds, most of the time the bus drivers continue their movement and clear the intersection if they are the first vehicle stopped when the light turns red. Considering the high proportion of buses (55 buses/hr, out of a total volume is 260 veh/hr), the green duration for that stream may be regarded as more than 16 seconds which can also affect the average travel time of the buses.
To account for drivers’ aggressiveness, the green duration was increased from 16 seconds to 17 seconds in the simulation. This change in green time decreased the model average travel time by 42.9 seconds. Figure 3-5 shows the results with modified green duration.

This one second increase in the green duration led to a significant decrease in the average travel time. If the two histograms based on the observed and recalibrated results are compared, the maximum travel time for both cases is 350 seconds, and the average travel times are quite close (214.5 and 208.2 seconds). The peaks are similar except that there is 20 seconds offset in the simulated results. This may have occurred due to the fact that in reality some of the buses are delayed by pedestrians violating the crossing rules at the main entrance of Ruggles MBTA Bus Terminal.
Because the study results are based on comparing a simulated base case against simulated alternatives, and the travel time results for the model are similar to real world condition, no further validation was performed.

### 3.4 Critique of Existing Signal Timing Plan, A.M. Peak

The existing control plan at the intersections around bus terminal appears to be based on minimizing vehicle-delay. It has a coordination plan that favors through traffic, not buses turning into and out of the terminal, and has unfavorable timings for minor turning movements that buses make. In the following pages, the existing signal timing plan is analyzed and the shortcomings of the control plan are discussed.

- **Signal Coordination Not Favoring Bus Traffic (Intersection #2 and #3)**

  The coordination strategy at the intersections of Ruggles Street – Busway Exit (#2) and Ruggles – Tremont – Whittier (#3) favors East Bound (EB) traffic on Tremont and both North Bound (NB) and South Bound (SB) traffic on Ruggles. For buses at the main entry/exit, 3 movements, namely South Bound Left (SBL), South Bound Right (SBR) (outgoing buses), and EBL (incoming buses), do not have a deliberate coordination and a large component of their delay is due to unfavorable offsets. Figure 3-6 illustrates the signal timing plans of the two adjacent intersections that carry the main bus movements.
Both of these intersections shown in Figure 3-6 are actuated-coordinated. For those two intersections, uncoordinated phases have a maximum green without a force-off (i.e., the extra time, which comes from gapping out of uncoordinated phases, goes to coordinated phases at the end of the cycle with an exception that if any all-pedestrian phase (i.e., pedestrians are fully protected by giving green only to pedestrians) immediately following the coordinated phase is skipped, its time goes to coordinated phase in the same cycle.

To emphasize the lack of coordination for buses, a “green wave” illustration for the main bus movements was developed. Figure 3-7 shows the progression of buses for an average-length Whittier phase, while Figure 3-8 and Figure 3-9 demonstrate for the
extreme cases (Pedestrian Call, which makes the Whittier phase longer, and Skipping of Whittier)

Figure 3-7 Outgoing Bus Movements from Terminal and Incoming Bus Movements to Terminal at Ruggles Street–Busway and Ruggles-Tremont-Whittier Intersections for Typical Whittier Street Phase (1 to 4 Vehicles) and No Pedestrians

The average travel time from the intersection at Ruggles - Busway (Intersection #2) to reach the downstream intersection (Intersection #3) is approximately 20 seconds. This implies that a bus starting its movement at time \(T=87\) arrives downstream intersection at approximately \(T=7\) and has to wait 23 seconds for the start of green at \(T=30\), plus additional delay in case there is a queue (note that the starting times of these two streams are fixed). In a similar manner, EBL buses clear Ruggles-Tremont-Whittier
intersection between T=70 and T=75 (they may start early due to gapping out of other streams) and reach the downstream intersection (Ruggles-MBTA Busway) just after it turns red at around T=90.

The length of Whittier phase is the main factor affecting the variable green start time for Tremont EBL. Figure 3-7 represents the most common case, where Whittier Street does not have a pedestrian actuation and gaps-out after about 10 s. The EBL green will start earlier if Whittier phase gets skipped, and later if Whittier has a pedestrian call. Figure 3-8 shows progression for buses when there is a ped call on Whittier, and Figure 3-9 displays the progression when the Whittier phase gets skipped.

Figure 3-8 Outgoing Bus Movements from Terminal and Incoming Bus Movements to Terminal at Ruggles Street–Busway and Ruggles-Tremont-Whittier Intersections for Whittier Street Maximum Green (Pedestrian Call)
Figures 3-8 and 3-9 indicate that EBL bus delay is reduced when the EBL phase starts approximately 10 seconds late due to a pedestrian call on Whittier St. (Figure 3-8), and higher when the Whittier phase gets skipped (Figure 3-9).

The progression diagrams for the buses using the main entry/exit indicated that lack of coordination is one of the main factors of bus delays, an issue that may be overcome by adjusting the signal timing plans accordingly.

- **Overflow for EBL at Ruggles–Tremont–Whittier Intersection**

  The green duration for the EBL approach is 16 seconds, which creates cycle overflows during morning peak. The vehicles joining the back of the queue during the
peak 15 minute period mostly cannot clear the intersection in the first cycle, increasing both car and transit delay excessively.

**Queue Spillback on Ruggles Street**

At the intersection of Ruggles Street-Busway, Ruggles Street’s NBT stream has only one lane. This NBT stream is fed by three traffic streams from the upstream intersection (intersection #3): WBR, EBL and NBT and requires good coordination to prevent queue spillback on Tremont Street. Figure 3-10 demonstrates queue formation on Intersection #2’s NBT approach when there is a pedestrian actuation at Busway.

![Signal Timing Plan](image)

**Figure 3-10 Queue Formation on Ruggles Street When Pedestrian Actuation at Ruggles Street-Busway Intersection**

The movement of WBR traffic at Tremont Street-Ruggles Street is coordinated with the NBT phase at the downstream intersection (Busway at Ruggles St.). However when there is a pedestrian call at Ruggles Street-Busway, NBT and EBL vehicles are
blocked at the downstream intersection due to pedestrian phase and bus phase. Fortunately, NBT volume is minimal (i.e., rarely more than 2 cars per cycle). On the other hand, considering the high volume on EBL stream (260 veh/hr), the high proportion of buses (e.g., greater vehicle length) and the closeness of the two intersections (320 ft), the queue on Ruggles St. sometimes spills to Tremont St. and blocks the WBR traffic. For an average length Whittier Phase (no pedestrian call and 1-4 vehicles) and max-out (i.e., an actuated phase uses its maximum green time) of Busway at Ruggles, the situation is aggravated by the greater number of WBR vehicles joining the queue due to an early start at Tremont.

With the existing splits, it is difficult to provide a better coordination plan since the green duration of NBT phase at Busway is much smaller than the total green duration of these 3 phases feeding the queue. This problem could be alleviated by increasing the green duration of NBT phase at Busway, which can be accomplished by eliminating all-ped phase and using concurrent pedestrian crossing at Busway (Section 4.3), and modifying the offsets.

➢ No Coordination for Back Entrance (Columbus Avenue – Melnea Cass Boulevard)

Ruggles Bus Terminal has also a back entrance that serves 22 incoming buses during the A.M. peak, 16 from Melnea Cass Boulevard and 6 from EB Tremont Street (See Figure 3-1). These buses need to clear two intersections, namely Tremont-Melnea Cass (intersection #5) and Melnea Cass Boulevard-Columbus Avenue (intersection #6), which are not coordinated, having cycle lengths of 100 seconds and 90 seconds respectively (Figure 3-11).
The existing signal timing plan favors main traffic stream (NBR) at Melnea Cass-Columbus Intersection (#6), which is green most of the cycle. However, the NBTL phase, which serves incoming bus routes, is served poorly, because it is not considered as one of the main traffic streams at intersection #6. Table 3-6 shows percentages of vehicles and percentages of travelers for conflicting groups at intersection #6 during A.M. peak.

<table>
<thead>
<tr>
<th></th>
<th>vehicles / hour</th>
<th>travelers / hour</th>
<th>green time allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBT</td>
<td>14.7%</td>
<td>9.1%</td>
<td>18.9%</td>
</tr>
<tr>
<td>NBTL</td>
<td>44.6%</td>
<td>65.9%</td>
<td>34.4%</td>
</tr>
<tr>
<td>WBL</td>
<td>40.7%</td>
<td>25.0%</td>
<td>46.7%</td>
</tr>
</tbody>
</table>

Table 3-6 Percentages of Vehicles and Travelers for Conflicting Groups, Melnea Cass Boulevard – Columbus Avenue Intersection

Even though the NBTL phase handles 65.9% of travelers, it has a short green (taking only 34.4% of green), and therefore long red, causing a long delay to NBT buses. Secondly, there is no coordination for bus movements because the cycle lengths of two
adjacent intersections are different (Figure 3-11). However, with the existing signal timing plan (fixed-time control), it may be difficult to coordinate for buses even if they have the same cycle length since 6 buses/hr come from WBR, while 16 come from NBT at intersection #5.

➢ **No Priority Tactics for Transit**

None of the intersections in the network has any TSP tactics to facilitate the movement of buses. The only place in the MBTA system in which buses are granted priority is on the Silver Line – Washington St (Section 2.1).

➢ **Long Cycles (Hurting both Buses and Peds)**

Except Melnea Cass-Columbus, all of the intersections around Ruggles Station have a cycle length of 100 seconds with coordination. A long cycle means a long delay for minor movements with short green periods. Without disrupting the coordination along the arterials, double cycles, in which minor phases come into realization twice during one cycle, might be applied in order to reduce the delays. In our study, double cycling for buses was applied at two intersections with different priority tactics (Sections 4.7 and 4.8).
Chapter 4: Tactics to Improve Operation of Buses Around Ruggles Bus Terminal

4.1 Introduction

This chapter explains signal control strategies to reduce bus signal delays around a major terminal, and how they were applied around Ruggles Bus Terminal. The priority tactics discussed in this chapter can be outlined as follows:

1. Passive Priority
   - Adjusting the splits to favor bus flows (Section 4.2)
   - Adjusting offsets and phase sequence to improve bus coordination (Section 4.3)
   - Reducing variability by preventing phase skipping and recalling pedestrian phases (Section 4.4)
   - Holding buses at the terminal (Section 4.5 – Not Applied)

2. Active Priority
   - Green Extension (Section 4.6)
   - Early Green – (Section 4.7)
   - Phase Insertion (Section 4.8)
   - Dynamic Phase Rotation (Section 4.9)

3. Flexible and Interruptible Control Logic
   - Dynamic Coordination (Section 4.10)
   - Free Actuated Cycling Within a Fixed Cycle (Section 4.11)
   - Floating coordination point (Section 4.12)
   - Fully actuated, cycle free (Section 4.13, Not Applied)
4. Compensation Strategies

- Aggressive priority with compensation (Section 4.14)
- Queue spillback prevention (Section 4.15, Not Applied)

5. Capacity Enhancements

- Replacing an all pedestrian-phase with concurrent walk and Leading Pedestrian Interval (L.P.I, Section 4.16)

Passive priority operates continuously and does not require any transit detection system. Some of the common passive priority applications include adjusting splits and offsets to favor buses and providing left-turning bus phases twice per cycle (double realization). Furthermore, operational improvements to signal timing plans, such as retiming, using shorter cycle lengths or coordinating signals on a corridor may improve traffic flow and reduce transit travel time as well and therefore is also regarded as passive priority treatments. In general, passive priority is an effective priority strategy when transit operations are predictable, with little variability in travel time and dwell time at transit stops.

The two most common active priority strategies include green extension and early green. These two methods are easier to apply to bus routes with limited frequency by extra green time or less red time to the transit vehicles when a bus is detected. However this may not be the best approach near a major terminal, because bus volume may be so high. Considering a situation/location with a large number of buses, interrupting a signal timing plan for every bus will have a huge impact on the non-priority traffic. Moreover, any improvement for a specific bus route might aggravate other transit routes since it is
most likely that there will be competing bus routes calling for a priority from other approaches.

Consequently, at intersections with high transit vehicle frequencies, developing effective passive priority strategies is important to limit active priority applications and to minimize disruption of general traffic. Active tactics can then be applied in specific situations to address and solve critical shortcomings of passive tactics.

4.2 Adjusting Splits to Favor Bus Flows

At intersections around a major bus terminal, many buses use minor phases with short green intervals to turn into or out of the terminal. Oversaturation or near saturation on those minor streams results in cycle overflows (vehicles have to wait a second cycle or more) and very long delays. Sometimes, giving these phases just a few extra seconds can reduce their delay dramatically without much impact on other phases. If the phases are actuated, that protects against green time being wasted, thereby creating an opportunity to increase the maximum green for the bus phase more generously, knowing that only the required green time will be used.

At the Tremont Street–Ruggles Street intersection, there is an overflow queue problem for EBL from Tremont to Ruggles where buses account for 21.2% of the left-turning traffic. The maximum green duration for this stream was increased from 17 seconds to 21 seconds to limit oversaturation. Simulation shows that adding 4 seconds to average phase length increased average green duration only 1.4 seconds, yet is very effective at limiting cycle overflow. As a result, EBL bus delay falls from 98.4 seconds to 67.3 seconds (Section 5.2.2).
4.3 Adjusting Offsets and Phase Sequence to Improve Bus Coordination

Generally, the coordination plan around a terminal will favor through movements on the arterial, not buses turning into and out of the terminal. At Ruggles station, most buses pass through two signalized intersections before joining, or upon leaving, the main coordinated arterials. Adjusting the offsets and phase sequence to provide green waves for the buses without disrupting the main flow of traffic can be regarded as a guide around a major bus terminal where frequencies are high.

The main pair of intersections that offset and sequence adjustments were performed to improve bus coordination are Ruggles Street-Busway (#2) and Ruggles-Tremont-Whittier (#3) (Figure 4-1).

**Figure 4-1 Recommended Signal Timing Plan, Ruggles Street-Busway and Ruggles-Tremont-Whittier Intersections**
The green time for EBL phase was increased from 16 seconds to 21 seconds to prevent oversaturation at the Ruggles-Tremont-Whittier (#3) intersection.

The sequence of SB and NB phases was reversed at intersection #3 and offsets were modified at both of the intersections.

Furthermore, a concurrent pedestrian phase instead of an all pedestrian phase with a leading pedestrian interval (LPI) of 3 seconds was applied at Ruggles Street- Busway intersection (#2) to increase the green duration for NB stream and to inhibit the queue spillback on Ruggles Street. LPI is a treatment to maintain pedestrian safety by allowing pedestrians to enter the intersection earlier than the bus phase, giving them an opportunity to establish a presence in the crosswalk. The walk period for the pedestrians was also increased from 7 seconds to 14 seconds to diminish the delay experienced by pedestrians.

Finally for the Busway at Ruggles, the minimum green was increased from 8 seconds to 18 seconds in order to accommodate the concurrent pedestrian phase (which has recall, no pedestrian actuation needed). The bus green may be terminated at T=57 if no bus is detected at the end of 18 seconds.

For all of the buses using intersections 2 – 3 (131 buses/hour), simulation results showed that the two passive priority strategies reduced average bus delay by 20 seconds per intersection.

<table>
<thead>
<tr>
<th></th>
<th>Average Bus Delay (seconds/bus/intersection)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>46.3</td>
</tr>
<tr>
<td>Adjusted splits</td>
<td>39.8</td>
</tr>
<tr>
<td>Adjusted splits, sequence + offsets</td>
<td>26.0</td>
</tr>
</tbody>
</table>

**Table 4-1 Bus Delay Times per Intersection, Ruggles Street-Busway and Ruggles-Tremont-Whittier Intersections**
4.4 Reducing Variability by Preventing Phase Skipping and Recalling Pedestrian Phases

With actuated-coordinated operation, the starting time of phases that follow actuated streams can vary considerably from cycle to cycle. For the main (through) movement phases, this is not a problem since they have a fixed coordination point at which the allocated green begins, even if their green begins earlier. But coordinating secondary phases becomes difficult when their start time vary a lot. A signal timing plan with green waves for buses may not actually provide the desired coordination if one phase starts late and the downstream phase starts early.

In our case study, the length of the Whittier Street (NBT) phase is the main variable affecting the green start time of bus phases, namely the SBR, SBL and EBL at intersection Ruggles-Tremont-Whittier intersection. In order to reduce the high variability of the starting time of those bus phases and to prevent the deterioration of green waves, skipping the Whittier phase was prevented, and its minimum split was increased from 8 seconds to 10 seconds, as shown in Figure 4-1.

With the passive priority changes described to this point, the following figure shows the progression of the heaviest bus movements, assuming a typical length Whittier (no pedestrians, 0 to 4 vehicles).
The coordination strategy favors the movement of EBL buses at the Ruggles-Tremont-Whittier intersection. For buses leaving the station and going left twice (busway to Ruggles Street, then Ruggles Street to Tremont), poor coordination can occur if the bus leaves the busway near the end of the allowed green. To illustrate, suppose a SBL bus clears the upstream intersection at $T=60$ and arrives Tremont at Ruggles at $T=80$ (allows a travel time of 20 seconds). This bus has to wait almost the entire red period to clear the second intersection (notice that this problem does not arise for SBR buses since they may turn right during the EBL phase).

This problem occurs when there is no pedestrian call for Whittier and a SBL bus arrives at the busway between $T=50$ and $T=64$. Considering the low volume of SBL
buses (22/hr) when compared to SBR (55/hr), the problem might be relieved by providing a green extension to SBL buses when they are detected on Ruggles Street.

Figure 4-3 demonstrates the main bus movements when there is a pedestrian actuation on Whittier Street, which lengthens the Whittier phase by 10 seconds.

Figure 4-3 Outgoing Bus Movements from Terminal and Incoming Bus Movements to Terminal at Ruggles–Busway and Ruggles-Tremont-Whittier Intersections for Whittier Street Maximum Green (Pedestrian Call)

In that case, the coordination plan favors almost all transit movements except a tiny portion at the end of the bus phase which is rarely used.

Even though the variation is reduced by preventing phase skipping and increasing minimum split on Whittier Street, variability in the signal timing plan still exists, necessitating some other strategies like green extension and dynamic coordination to accommodate better movements for all transit vehicles.
The above diagrams verify that recommended plans provide good coordination for bus movements. However, please note that when there is a queue spillback on Ruggles St from intersection #2 (busway) extending southerly along Ruggles St. to intersection #3 (Tremont), this will create gridlock impacting all vehicles, including buses. Therefore, the queue formation at Ruggles Busway was also considered in designing the recommended timing plans. Figure 4-4 exhibits the queue formation on Ruggles assuming a typical length Whittier phase.

**Figure 4-4 Queue Formation on Ruggles Street at Ruggles Street-Busway Intersection for Typical Whitter Street Phase (1 to 4 vehicles) and No Pedestrians**

The main traffic streams contributing to queue formation are the WBR and NBT. Terminating the green for NBT and starting busway phase at the Ruggles Street-Busway intersection (#2) when NBT traffic arrives from the downstream intersection (i.e., Whittier Street) is critical since Whittier Street releases at most 2 cars per cycle. Alternatively, the contribution of the WBR phase to queue formation on Ruggles Street at
Ruggles Street-Busway intersection (#2) is quite high. As it is seen the last few seconds of the leading WBR phase, the first 10-15 seconds of the lagging WBR phase and the entire NBT phase feed the queue on Ruggles St. However, the fact that Ruggles Street-Busway (#2) NBT phase usually starts earlier, at T=60 rather than T=68, can be regarded as a remedy for lagging WBR traffic (Figure 4-4).

Even for the extreme case (max-out of busway phase), it is expected that the queue rarely reaches Tremont St. To illustrate, considering an average spacing of 25ft per car (car length of 20 ft and a spacing of 2.5 ft on each end of the vehicle), since the block is 320 ft long, 13 cars can fit between these adjacent intersections. It is known that at most 2 vehicles in each cycle go through from Whittier to Ruggles. Considering a 2.5 sec headway for WBR traffic due to the effect of right-turning geometry, 8 WBR cars will join the queue making totally 10 cars at the end of red period. Alternatively, this methodology is sound if all of the vehicles are passenger cars. If a bus or tow, or a heavy vehicle is in the traffic stream, then the number of vehicles in the queue decreases. Fortunately the bus and heavy vehicle proportion is only 3% for these two streams and therefore it is concluded that the buffer is sufficient to prevent queue spillback.

In the simulation model, the queue very rarely extends from Ruggles Street to Tremont Street and as a result average delay for WBR and EBL vehicles is significantly reduced.

4.5 Holding Buses at the Terminal

Buses leaving the terminal have a 25 second window in every 100 seconds cycle in which they can turn left onto Ruggles St. One approach to reducing delay is to hold the buses at the terminal. This approach forces the buses to enter the first intersection during
the green interval. In one sense this strategy only shifts delay from the intersection to the terminal. However, the fact that passengers can still get into the bus makes waiting at the terminal productive by reducing passenger waiting time.

To give an example, during each 100 seconds cycle buses get almost 25 seconds green at the first intersection when they clear Ruggles Terminal. Using in-station or in-vehicle signals provides drivers with a window of approximately 30 seconds in each 100 second interval to depart. Since pedestrians cross with the buses concurrently at the first intersection, releasing buses little earlier than the green interval might be a good method to increase pedestrian safety, thereby making buses slow down before getting into the first intersection.

However in spite of the benefits in reducing the bus delay at the first intersection, holding strategy was not considered in this study due to challenges in field application.

### 4.6 Green Extension

As opposed to the passive priority tactics operating continuously regardless of whether transit is present or not, active priority provides special preferential treatments to the transit vehicles based on the detection. Sections 4.6 – 4.9 present various types of active priority strategies and their spot application in this study.

Green extension means extending the green time beyond the normal maximum green when a transit vehicle approaching the intersection is detected. Green extension offers a big benefit for buses that use the priority extension by reducing their delay from the entire red period to zero. Alternatively, only a small fraction of buses can take advantage of this method, those arriving in what would normally be the first few seconds of red.
The fact that green extension applies to only a small fraction of buses (i.e., only buses that are predicted to arrive at the end normal maximum green, but before the maximum extension time) makes it an ideal TSP strategy to use where bus volumes are high.

In this study, green extension was tried for three different approaches with different transit priority logic at the Ruggles-Tremont-Whittier and Tremont Street-Melnea Cass Boulevard intersections. Two of those approaches (EBL and SBL) are at the intersection of Tremont-Ruggles-Whittier, Intersection #3 (Figure 4-5).

![Figure 4-5 Location of Detectors for Green Extension at Ruggles –Tremont -Whittier Intersection for East Bound Left & South Bound Left Buses](image)

Both check-in (extension or call) and check-out (cancel) detectors were used to call for priority and to cancel priority respectively. For the EBL, check-in detector was placed 390 feet upstream of stopline corresponding to approximately 10 seconds of travel time for EBL buses assuming a bus speed of approximately 25 miles per hour (mph). For SBL buses, the check-in detector was located after the stopline at the busway intersection; about 9 seconds travel time upstream. Maximum priority extension for EBL
and SBL buses is 10 seconds and 5 seconds respectively. Both of these phases are actuated and in case the bus hits the check-out detector before the full extension has timed, the extra time is given to the coordinated (EBT-WBT) phases.

Transit Priority Logic

Application of green extension in the simulation model at the Ruggles-Tremont-Whittier and Tremont-Melnea Cass Boulevard intersections is explained as follows:

- If a bus is projected to enter the intersection during the normal green interval, no extension is performed to the signal timing plan.
- If a bus is projected to arrive after the end of green but within the specified extension interval, the green interval is extended until either the bus clears the intersection or the maximum specified duration is reached. The required extra green time is taken from the WBT phase.
- A force-off point in the cycle at which the priority calls are cancelled is provided to maintain minimum green constraints.
- No changes are allowed to the cycle length in order to preserve coordination with the adjacent intersections.

Figure 4-6 Signal Timing Plan at Ruggles-Tremont-Whittier Intersection In Case of Green Extension, Assuming a Typical Whittier Street Phase
At the intersection of Ruggles-Tremont-Whittier, there is a force-off point at which the priority calls are cancelled to provide 14 seconds of minimum green time for WBT traffic. Moreover to prevent oversaturation that could put intersection into gridlock, impacting not only the non-transit traffic but also the buses. Thus, the maximum extension for EBL approach is 10 seconds unless the extension reaches force-off point, in which case maximum extension is reduced accordingly. However it should be noted that the force-off application can only occur when both SBL and EBL phases use their maximum priority extension in the previous cycle, something that rarely happens.

The forcing-off is more likely to occur when previous cycle has a pedestrian call on Whittier Street (Figure 4-7).

![Figure 4-7 Signal Timing Plan at Ruggles-Tremont-Whittier Intersection In Case of Green Extension and Maximum Whittier Phase (Ped Call)](image)

It is seen that the force-off here limits the extension for EBL buses to only 4 seconds. This problem in reality is not crucial due to the fact that the pedestrian volume is low and the SBL stream might end early, allowing EBL start earlier, thereby increasing the maximum allowed extension for EBL buses.

It should also be noted that the priority extension for SBL buses are not displayed in the above diagram since there is a good progression for SBL bus movements when
there is a pedestrian call on Whittier Street which does not necessitate green extension (Figure 4-3).

For all of the different extension scenarios, the green time is taken from WBT phase, which may cause negative impacts on traffic. Fortunately priority approaches are actuated and buses operate in mixed traffic. Giving a bus priority therefore means generally giving priority to regular non-transit traffic. The priority system acts like a bulldozer, pushing ahead any cars that are queued up in front of a bus, helping the compensation of WBT phase in the next cycle as explained in the following paragraph.

To illustrate, consider the situation when a check-in detector on EBL approach is actuated by a bus while the queue on the left-turning lane has almost spilled back to the through lane (Figure 4-5). In that case, the priority extension first operates for normal traffic, extending the green and pushing all the traffic in front of the bus and then holds the light green until the bus clears the intersection. As a result in the next cycle it is expected that fewer cars will arrive and priority approaches will gap-out sooner, increasing the green duration of WBT approach.

Simulation results showed that EBL buses were granted green extension 21.3% of the cycles. Despite the fact that probability of green extension is quite high, the increase in average green duration for EBL is only 0.3 seconds, justifying our prior expectations. Extended phases not only serve for transit but also for normal traffic, decreasing the number of cars in the following cycle, increasing the chance of gapping-out for actuated streams, and letting WBT begin earlier, thus compensating this non-priority stream.

As explained in Section 4.2, split adjustments reduced EBL bus delay from 98.4 seconds to 67.3 seconds and green extension further reduced the delay to 55.1 seconds
with no detectable impact on WBT traffic. Even though green time for extension is taken from WBT; the compensation effect of actuation has the result that average green duration of WBT is reduced by only 0.5 seconds, from 30.3 seconds to 29.8 seconds.

The last intersection at which green extension was tested is Tremont Street–Melnea Cass Boulevard (Intersection #5), for NBT buses. The priority logic the same as given for Ruggles-Tremont-Whittier intersection (but without a force-off) and specified green extension is 10 seconds. The signal timing plan in case of green extension and layout of the intersection are shown in the following figure.

![Signal Timing Plan at Tremont-Melnea Cass Boulevard Intersection with Green Extension](image)

Check-in detectors and check-out detectors were located to request and to cancel priority. Note that the location of upstream detectors is further from the stopline than it is for EBL buses, because the speed for through buses (i.e., the NBT buses at the
intersection of Tremont Street-Melnea Cass Boulevard) is higher than the speed for left-turning buses (i.e., the EBL buses at the intersection of Ruggles-Tremont-Whittier).

The worst-case scenario in which the priority extension is completely utilized and there is a pedestrian call, WBT gets 13 seconds of green time. When there is no pedestrian actuation (considering the relatively low ped volume on SB phase), SBT mostly uses its minimum time and the extra time goes to EBT-WBT approaches, which helps compensating the WBT approach.

Simulation results indicated that green extension occurs in 5.6% of the cycles with a great reduction in NBT bus delay. Green extensions diminished NBT bus delay from 41.5 seconds to 33.7 seconds without disrupting the general traffic.

4.7 Early Green

Early green (red truncation) shortens the green time of preceding phases, and possibly skips preceding phases, to hasten the return to green for the transit movement in which priority is requested. The U.S. typical application applies early green when the predicted arrival of transit is during a red phase. However, it could also benefit transit vehicles in mixed traffic arriving on green, but within the queue clearance interval. The goal in the latter case is to start the green before the bus arrives to clear the queue so that when the bus arrives, the signal will be green and there will be no queue in front of the bus. However, this strategy requires more sophisticated intelligence like queue length tracking and advanced transit prediction methods.

Unlike green extension, the reduction in delay due to early green would not be dramatic; however the proportion of transit vehicles that could benefit from this tactic is quite high since the duration that an early green can be requested by a bus within a cycle
is much higher compared to green extension. That makes early green an excellent tactic for intersections with infrequent bus service, but at intersections with frequent buses, it would be impractical to grant early green in a high proportion of cycles.

Therefore, throughout this study, early green was generally not considered due to its huge impact on general traffic at the intersections with high bus volume. The only intersection that early green was tested is Melnea Cass Boulevard-Columbus Avenue (#6), where buses get into the terminal using the back entrance, because of its moderately low traffic demand, providing an opportunity to develop highly interruptible signal controllers that can accommodate priority for large number of buses. (Figure 4-9)

**Figure 4-9 Early Green at the Intersection of Melnea Cass Boulevard-Columbus Avenue**

**Transit Priority Logic for Downstream Intersection (Intersection #6)**

The developed methods to apply early green tactic in the simulation model is given as follows:
• Approaching buses are detected at the upstream intersection right after the stopline (2 detectors for 2 different transit approaches)

• A fixed point in the signal timing plan at T=76 is provided, when EBT begins. It runs to its maximum time only if there is pedestrian actuation and uses its minimum split otherwise. The reasons a fixed starting time for EBT phase is used at T=76 in each cycle is to also maintain the coordination between intersections #5 and #6, which is going to be discussed in Sections 4.10 & 4.11.

• The other two phases run freely similar to a fully-actuated controller. For the non-transit vehicles that use NBL phase, calls are delayed (detector makes a call after it has been occupied more than 6 seconds) since the queue at this intersection is fed by vehicles that use a protected + permitted phase at the upstream intersection and therefore arriving with gaps rather than arriving in platoons for certain amount of time.

• If a bus is detected while the bus phase is running at the intersection of Melnea Cass Boulevard-Columbus Avenue, the light is held green until the bus clears the intersection.

• If a bus is detected while traffic on other approaches is green, early green is applied. The green for the running phase is terminated as soon as the minimum green requirement is satisfied, and the bus phase begins.

Typical signal controllers in U.S. cannot respond to real-time traffic and transit conditions with this level of flexibility, which limits priority applications in high frequency bus routes. At the back entrance, even though the bus volume is quite high (22 buses/hr), early green was applied aggressively (only minimum green time is given to
non-bus phases when a bus is detected) with no impact on the side traffic through the usage of highly interruptible traffic signal control.

Simulation results indicated that early green incorporated with other strategies reduced average bus delay from 20.9 seconds to 7.4 seconds, and reduced average vehicle delay from 22.0 seconds to 14.9 seconds. The benefit for overall traffic comes from using fully-actuated control, resulting in short red periods.

### 4.8 Phase Insertion

Phase insertion is the insertion of a special priority phase within the normal phase sequence when a transit vehicle is detected. Around a major terminal, many buses use minor turning phases with small green intervals to get into and out of the terminal. Preventing oversaturation is one of the key remedies to decrease bus delay on those approaches by maintaining undersaturated conditions and preventing overflow. Being a minor approach, however, left-turning vehicles including buses still experience considerable delay because of the long red times on minor streams, even if they are able to clear the intersection in the first cycle. Phase insertion can play an important role by reducing effective red time, thereby decreasing transit delay.

In this study, phase insertion was tried at Ruggles-Tremont-Whittier Intersection (Intersection #3) for EBL buses. The signal timing plan when phase insertion is applied is shown in Figure 4-10.
While the buses have to wait up to three phases for the green light in the standard phase sequence, phase insertion reduces it to two phases. Note that there is also a priority extension of five seconds for the inserted phase if any bus is projected to arrive within this extension interval.

**Transit Priority Logic**

Phase insertion for EBL buses at the Ruggles-Tremont-Whittier intersection is applied in the simulation model if the following criteria are satisfied.

- Phase insertion is performed if a transit vehicle is detected at $T=26$ in the cycle and there is no pedestrian call on Whittier Street (Figure 4-10).
- Approaching buses are detected at 150 ft upstream of the stopline. The distance is specified such that if the bus is the last vehicle in the queue actuating the insertion detector, it is able to clear the intersection when a phase is inserted (may or may not use the priority extension of 5 seconds).
- Green (priority) extension of 10 seconds for the primary phase still applies.
• Priority extension of 5 seconds is also considered for the inserted phase.

• There is a force-off point in the plan to provide 14 seconds of minimum green for WBT approach and in order to keep the cycle length fixed.

Figure 4-10 points out the risk of a minimum-length WBT phase that might occur if phase insertion is applied and the primary EBL approach uses its maximum split in successive cycles. However, as with green extension, because buses operate in mixed traffic, the inserted phase also serves the non-transit traffic, decreasing the likelihood that the primary EBL will use its maximum split in the following cycles.

The following table presents average durations of the EBL phases under different priority schemes.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Green Extension (s)</th>
<th>Green Extension &amp; Phase Insertion (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary EBL</td>
<td>18.1</td>
<td>14.7</td>
</tr>
<tr>
<td>Inserted EBL</td>
<td>-</td>
<td>4.4</td>
</tr>
<tr>
<td>Average EBL</td>
<td>18.1</td>
<td>19.1</td>
</tr>
</tbody>
</table>

\[
p^\text{*(extension)} = 0.213 \\
p^\text{*(insertion)} = 0.386 \\
p^\text{*(extension)} = 0.0777
\]

\[p^* = \text{percentage that a priority scheme occurred in the simulation model}\]

Table 4-2 Average East Bound Left Phase Durations under Green Extension and Phase Insertion

Under tested conditions, phase insertion is applied 38.6% of the cycles. When applied, the duration of the inserted phase is 11.5 seconds on average. Considering all cycles, the average time consumed by the inserted phase is only 4.4 seconds, or 4.4% of the cycle. However, because it is an actuated approach, that does not increase the total time per cycle for 4.4 seconds. Because of the reduction in the number of vehicles that
use primary EBL phase that follows inserted phase, average primary green duration was decreased by 3.4 seconds, from 18.1 seconds to 14.7 seconds, attributable to actuation. So, the net impact on average EBL is only 1.0 second per cycle, which demonstrates another example of compensation.

Simulation results indicated that phase insertion reduced average EBL bus delay at this intersection from 55.1 seconds to 33.0 seconds. However, buses benefiting from phase insertion had greater delay than usual at the downstream intersection (Intersection #2) because the bus coordination plans were designed to provide green waves for the transit vehicles using primary EBL approach, not the inserted one (Figure 4-11).

![Diagram of signal timing plan and bus movements](image)

**Figure 4-11 Outgoing Bus Movements from Terminal and Incoming Bus Movements to Terminal In Case of Phase Insertion at the Intersections of Ruggles-Tremont-Whittier and Ruggles Street-Busway**
EBL buses that use the inserted phase at the Ruggles-Tremont-Whittier intersection (#3) start their turning at $T=30$ and arrive the next intersection (#2) at approximately $T = 45$ (Figure 4-11). Note that the signal is red for NBT buses at $T=45$ at the Ruggles Street-Busway intersection and green for competing stream (i.e., WBL) to serve pedestrians and buses leaving the terminal. Hence, the buses use the inserted phase at Ruggles-Tremont-Whittier intersection hit the red light at the downstream intersection (#2). Furthermore, buses leaving the terminal experience a small delay at the downstream intersection due to lagged start of the SB phase. However, the delay that comes from these disruptions to bus coordination is smaller than the direct benefit of phase insertion, yielding a substantial net reduction in origin-destination bus delays.

4.9 Dynamic Phase Rotation

When a transit vehicle is projected to enter an intersection during the red period, the order of the signal phases can be rotated to reduce the red time and delay of transit. While several German cities and Zurich have been applying phase rotation for many years, it is not a common tactic in North America due to the perception that rotation violates driver expectancy and creates confusion among motorists and pedestrians. Although that might be true to some extent, it is mainly the cyclists and pedestrians that are affected by phase rotation, and not the drivers who basically follows the signal head and waits for the onset of green.

At our site, phase rotation seemed appropriate only for the junction Tremont – Melnea Cass (Intersection #5). The modified signal timing with rotation is shown in Figure 4-13.
Transit Priority Logic

Application of phase rotation at Tremont Street-Melnea Cass Boulevard can be given as:

- Two different detectors were used to check-in transit vehicles.
- Rotation is accomplished if:
  - A call detector, 420 ft upstream of stopline, is activated during Phase 1 or Phase 4. There is no travel time projection in that case and the call detector tracks the buses in the queue waiting for a green and rotates the signal phases to reduce the red time.
  - An advance detector, 1300 ft upstream of stopline, projects that bus arrival will fall during Phase2 and a pedestrian call is present for crossing Tremont. It is known
unless there is pedestrian actuation; Phase 2 rarely uses more than its minimum time, resulting in an earlier start for Phase 3 (bus phase). Thus, it was decided not to rotate the phases if there is no pedestrian call even if a bus is projected to arrive during Phase 2 in order to minimize the impact on the traffic.

Phase rotation does not directly cause any capacity reduction because green time of any phase is not reduced to accommodate phase rotation. Alternatively, rotation introduces some variability in red time that vehicles experience by altering the order of the signal phases in some cycles but not in others. While some vehicles experience less red time due to phase rotation, some experience more if a normal phase follows a rotated phase. Phase rotation also interrupts coordination, and can potentially result in queue spillback or starvation (in which signal is green at downstream intersection but not used by any vehicles since vehicles are not released from upstream intersection), indirectly affecting capacity.

Simulation results showed that phase rotation reduced average NBT bus delay from 33.7 seconds to 26.9 seconds (assuming green extension applies in both cases), and caused no significant impact to general traffic.

Passive and active priority tactics point out that large reduction in transit delay might be obtained using aggressive priority tactics along with flexible and highly interruptible control logic, responding quickly to and recovering quickly from priority interruptions. Compensation is one of the keys to flexible control logic that should be taken into account in order to practice effective TSP with minimal disruption to general traffic.
Unfortunately, in the United States, standard control logic for TSP does not include compensation, resulting in poor priority tactics that reduce the effectiveness of TSP as traffic engineers protect general traffic from over capacity.

For the rest of this chapter, some additional priority tactics are described to enhance the performance and overcome the weaknesses of previously described strategies. Firstly, some of the key tactics to create flexible and interruptible control logic are discussed in Sections 4.10 – 4.13. Compensation strategies to minimize the impact of signal priority are explained in Sections 4.14 – 4.15 and finally capacity enhancement methods are presented in Section 4.16.

### 4.10 Dynamic Coordination

Signal coordination (green wave) is usually provided by keeping intersections on a fixed cycle, with (near) fixed phase start times. Priority interruptions then become very disruptive to coordination. With dynamic coordination, neither cycle lengths nor start times are fixed. Instead, signal controllers communicate peer-to-peer and each signal’s start of green becomes a request to the downstream signal resulting in spontaneous green waves [11].

Throughout this study, dynamic coordination of the whole network was not applied, because the four intersections in the study area are part of a larger network whose coordination (with a fixed cycle) is wanted to retain. However, we did include spot applications of dynamic coordination were included to create green waves for bus movements when priority or actuation at one intersection would have resulted in poor progression through the next.
At Intersection #2 (Ruggles-Busway) and Intersection #3 (Ruggles-Tremont-Whittier), there is good progression for SB buses unless the approach at Intersection #3 is terminated early due to gap-out (Figures 4-2 & 4-3). In order to maintain bus coordination, buses are detected right after the stopline at Intersection #2 and the termination of SB green at Intersection #3 is prevented until the bus clears the stopline.

A second application of dynamic coordination for buses was applied between Intersections #5 & #6 (Figure 4-9). To accomplish this, check-in detectors were located downstream of the stopline at the upstream intersection (Intersection #5) and once a detector is actuated by a bus, it sends a priority request to the downstream intersection (Intersection #6) in order to provide green wave for the buses.

4.11 Free Actuated Cycling Within a Fixed Cycle

This strategy involves combining the advantages of full actuated control with signal coordination by constraining cycle length for the main traffic movement. Full actuation with signal coordination was applied at Intersections #5 (Melnea Cass-Tremont) & #6 (Melnea Cass-Columbus) (Figure 4-1)
The main movement between the two intersections is D-E, with considerably high volumes. The objective is to ensure that those two movements coordinated, while letting Intersection #6 almost run cycle-free so that it can respond to priority requests to buses, arriving from both A & B (and therefore arriving in different parts of the cycle, making it hard to justify fixed coordination for both bus movements).

Movement C (essentially a driveway exit) and its corresponding pedestrian movement are permitted to a part in the cycle (T=76) when neither D nor B is running (Figure 4-9), and when it will not starve movement F. This provides the desired coordination for the main movement D-E, because movement E, being a right-turn movement, can run with any phase in a cycle except for C, and no vehicle arrive from D while C is running.

Other than a fixed start for EBT at time 76 in the 100-s cycle, the other two phases run free, changing as often as it gaps out to serve the other (if it has a call). Because of the relatively low traffic and pedestrian demand, the result is that those two phases are often realized twice, and sometimes three times, in each 100-s cycle. Table 4-3 shows the frequency of free phases running in a cycle at the back entrance during an hour period based on the simulation results.

<table>
<thead>
<tr>
<th>realizations per cycle</th>
<th>NBTL (used by bus)</th>
<th>WBL</th>
<th>Early Green</th>
<th>Green Extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68</td>
<td>81</td>
<td>67</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>229</td>
<td>205</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>53</td>
<td>63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>average realizations per cycle</td>
<td>1.90 phases/cycle</td>
<td>1.89 phases/cycle</td>
<td>6.7 interruptions/hour</td>
<td>3.0 interruptions/hour</td>
</tr>
</tbody>
</table>

Table 4-3 Frequency of Free Phases in a Cycle at the Melnea Cass Boulevard-Columbus Avenue Intersection
According to the simulation results, during a cycle both of the phases run almost 2 times on average, decreasing red time and therefore reducing both car delay and bus delay. This also makes the signal control flexible and highly interruptible, so that can easily respond to priority requests without disrupting general traffic.

4.12 Floating Coordination Point

In establishing a coordination plan, the first requirement is that all the coordinated signals have to operate with the same cycle length. Therefore the general practice is finding the most critical intersection along the arterial that requires the greatest cycle length and then designing the rest of intersections with that cycle length. Once the cycle length is determined, offset and split adjustments are performed to provide signal coordination.

In typical actuated-coordinated logic, all the extra time that comes from gapping-out of actuated phases is given to the coordinated movement. There are often fixed points in the cycle to terminate the green of the non-coordinated phases, guaranteeing the start time for the coordinated phases in each cycle. This coordination logic creates rigid control that can not recover quickly from priority interruptions, preventing compensation of interrupted streams and limiting priority applications.

At the intersection of Tremont-Ruggles-Whittier, floating coordination point logic was applied, which permits altering the starting time of the coordinated phase to accommodate aggressive priority tactics. In order to apply phase insertion tactic for EBL buses, it was allowed to start the coordinated phase up to 4 seconds late. This small change will not disrupt main coordination plan, while offering buses a large delay.
reduction. When a late start is used, a short green occurs for the coordinated phase; however, because the coordinated phase gets all the slack time in each cycle, it can handle the late start in occasional cycles because of the early start it gets in other cycles.

The normal starting time for the coordinated stream (EBT) is $T=83$ and it will start earlier if the preceding streams gap-out. The Whittier usually uses its minimum split, providing some extra time to the coordinated phase which facilitates the provision of priority if flexibility at the starting time of coordinated phases can be attained. Thus, in the signal timing plan floating coordination point was allowed to start the coordinated stream later in some cycles to provide phase insertion rather than starting at $T=83$ (Figure 4-10).

### 4.13 Fully Actuated, Cycle Free

Full actuation provides green time to the approaches based on detected traffic demand and therefore operates efficiently, especially when traffic demand over different approaches fluctuates over a wide range. Unlike under a coordinated plan, there is no background cycle; cycle length varies in each cycle depending on the traffic demand, giving the controller more freedom to operate, and resulting in short cycles that keep delays short.

Being much more flexible, fully actuated cycle free controllers can more easily accommodate aggressive priority tactics, especially at intersections with high bus volumes, since they have the ability to detect and serve unexpected queues caused by priority interruptions, thereby providing natural compensation to interrupted phases. Actuation naturally provides compensation because it switches from approaches with no flow or low flow to approaches with a queue that is ready to go at saturation flow.
4.14 Aggressive Priority with Compensation

Priority interruptions can lead to overflows and long queues on the interrupted streams as green times are extended or truncated. Queue overflows can cause excessive delays for motorists and transit routes on the affected side streets; especially if queues spillback into upstream intersections, causing gridlock. Thus, compensation strategies play a vital role in mitigating impacts of priority.

Typically, in green extension, green time is stolen from non-priority phases and it is not returned to the phases whose green is shortened. As a result, typical control has no compensation, and therefore uses timid or weak priority.

Our approach instead is aggressive priority with compensation, so that phases whose green is truncated in one cycle by a priority action can get long enough green to clear their resulting queue in the next. This is not done by formula, but using actuation logic.

To illustrate, as explained previously in Section 4.6, green extension offers a great benefit for EBL buses at Intersection #3 (Ruggles-Tremont-Whittier), and only increases average EBL green duration by 0.3 seconds, because in the cycles that follow green extension, less number of EBL vehicles arrive, and actuation logic terminates EBL green earlier, letting WBT (non-priority) start earlier, and thus providing natural compensation for WBT (non-priority) phase. Like green extension, phase insertion reduced average EBL bus delay considerably, and only increased average EBL green by one second, with also serving non-priority traffic in the phases inserted for buses, thereby increasing the likelihood of gapping-out of EBL in the next cycle. Those two priority applications point out that, even though there is not direct compensation logic in our study specified by a
formula, actuation logic naturally provides compensation, and minimizes the impact of TSP on non-priority phases.

In addition to compensation, check-out detectors and force-off point were used in order to limit priority impacts on interrupted streams. Check-out detectors have the greatest value when detection areas are far in-advance of a traffic signal, increasing the variability in estimated arrival time. Instead of extending the green for a fixed amount, check-out detectors could allow long extension times for slow buses and could terminate the green early for faster transit vehicles. As a result, check-out detectors increase the effectiveness of green extension and avoid wasted green time (Figures 4-5 & 4-8).

Finally force-off points, which specify beginning or ending of the permissive periods, were considered to guarantee providing minimum split times for non-priority phases and to inhibit overflow queues on those approaches.

4.15 Queue Spillback Prevention

At closely spaced intersections, overflow queues could spillback into upstream intersections, causing gridlock and dramatic reductions in intersection capacity, hurting all vehicles including buses. Where priority interruptions might lead to long queues, queue spillback should be prevented.

One common solution is spillback detectors, which can serve as priority inhibitors. Loop detectors can be placed near the spillback point. Once the queue reaches those detectors, all priority requests are cancelled until the queue dissipates; it is also possible to force a longer green, as done in some coordinated control schemes.

An earlier generation study of this site included the application of spillback detectors for WBT phase on Tremont in order to inhibit queue spillback from Intersection
#3 (Ruggles-Tremont Whittier) to Intersection #5 (Tremont-Melnea Cass), which can be
arised due to phase insertion [21]. The detectors are placed 127 ft downstream
Intersection #5, and if the detectors are occupied more than 5 seconds, then WBT is
considered to be highly congested, and any request for phase insertion is rejected and the
green time for WBT is extended to 31 seconds from 17 seconds. The simulation results
indicated that highly congested situation occurred 16% of the time during the entire
simulation period.

In our study, as explained previously, this strategy was not applied since actuation
logic provides natural compensation for WBT, preventing the necessity of spillback
detectors. For implementation, however, it is recommended to consider including
spillback detectors for those few occasions when it might be needed.

4.16 Replacing an All-Pedestrian Phase with Concurrent Walk and
Leading Pedestrian Interval (L.P.I.)

The last general approach to TSP is capacity enhancements, which create more
opportunity for buses to pass through traffic signals unhindered. Capacity enhancement
methods include roadway widening and traffic signal modifications. Providing extra
lanes at the intersections or inserting exclusive bus lanes in the network for transit
vehicles improve traffic flow and decrease both car and transit delay. However, in urban
areas, roadway widening is difficult to implement due to limited space and strict policies
that prevent intersection reconstruction. Consequently, signal modifications play an
important role while improving capacity of intersections.
In Section 3.4 it was mentioned that at Ruggles-Busway intersection, there exists one lane for northbound traffic which necessitates good coordination to prevent queue spillback. As seen in Figure 3-9, the existing coordination plan at Intersection #3 (Ruggles-Tremont-Whittier) favors WBR traffic, which constitutes 61% of incoming traffic from Tremont St. WB. However, NBT and EBL traffic often get stopped by a red light when they reach the busway. Considering the closeness of two intersections, the queue sometimes backs up to Tremont St.

Inserting an extra NB lane on Ruggles St. could be a remedy to increase both storage and throughput capacity; however at this intersection, a lane change assignment has already been implemented, so that Ruggles St. has 3 lanes SB and 1 lane NB, and the SB approach needs all three of those lanes in order to prevent overcapacity at Intersection #3.

In the existing signal timing plan, field observations revealed that despite the fact that pedestrians have an all pedestrian phase, they also use the bus phase that follows all pedestrian phase when they find a gap to cross the street. To take advantage of this, we applied a concurrent walk with L.P.I. in place of the existing all-pedestrian phase in order to increase the capacity and prevent queue spillback. This change also reduces average pedestrian delay (assuming peds obey the Walk signal).
Chapter 5: Evaluation of Simulation Results

5.1 Introduction

This chapter provides evaluation of different scenarios using delay time measurements and green time distributions. The results are presented in two different sections. In the first part, priority tactics are assessed at every intersection by making a before priority and after priority study using green time distributions of phases, which are affected by priority, and delay results. In the second part, delay results are compared for origin-destination pairs in the simulation model, which consist two to four intersections.

VISSIM was used to evaluate several scenarios to identify the benefits and impacts of TSP application. VISSIM can generate delay data for networks and delay is obtained by subtracting the unimpeded travel time (i.e., no other vehicles, no signal control) from the observed travel time [17]. In the simulation runs, a minimum 5 different random seeds were used data to account for stochastic variation of input flow arrivals throughout the analysis. In cases where there was a significant variation in the results (e.g., coefficient of variation is greater than 0.2), the number of random seeds was increased to reduce the variation and to get reliable results.

For the rest of the chapter, a standard abbreviation is used to describe different scenarios.

Early Green: EG  Phase Insertion: PI  Phase Rotation: PR
5.2 Intersection Delays

In order to evaluate the effectiveness of TSP, the delay results obtained from the simulation model at four intersections, at which priority was applied, are provided in the following section.

5.2.1 Ruggles Street – Busway (Intersection #2)

At this intersection only passive priority tactics were implemented to provide green waves for incoming bus routes and to prevent queue spillback on Ruggles St. Replacing an exclusive pedestrian phase with concurrent walk phase (pedestrians cross the street when traffic is moving in the direction of pedestrians) and adjusting the offsets to favor main bus movements are the two applied passive priority strategies at this intersection.

![Figure 5-1 Impact of Passive Priority Tactics on Bus, Vehicle and Person Delay at Ruggles Street-Busway Intersection](image)

Passive priority not only decreased average bus delay, but also non-transit delay by providing good coordination for all travelers (Figure 5-1). Application of concurrent pedestrian phase with LPI instead of an exclusive pedestrian phase increased the capacity.
of the NBT approach and prevented queue spillback, which reduced average vehicle
delay by 6.5 seconds (12.4 seconds to 5.9 seconds). Improved coordination for the buses
countneder Tirlnq from NSt Trewont Street (EBL Buses, Figures 4-2 and 4-3) helped reducing
average bus delay by 12.1 seconds (31.7 seconds to 19.6 seconds). Finally, passive
priority adjustments reduced average person delay by 10 seconds where average person
delay results were obtained assuming bus occupancy of 20 and car occupancy of 1.15.

5.2.2 Ruggles Street – Tremont Street – Whittier Street (Intersection #3)

This is one of the main intersections at which bus volume is very high (131
buses/hour) and buses experience significant delay in existing case (approximately 60
seconds of average bus delay). Therefore, several different priority tactics were applied to
reduce average bus delay. Priority strategies at this intersection include passive priority,
green extension and phase insertion and those strategies were applied incrementally, not
independent of each other.

In this section firstly, green time distributions of prioritized phases are provided
and compared to understand how priority applications on mixed traffic affect green time
distribution of actuated phases. Then bus delays and vehicular delays are presented for
different approaches as well as different vehicle classes.

The following figure demonstrates the green time distributions at the intersection
of Ruggles-Tremont-Whitter under base case and passive priority (split adjustments to
prevent overflow queues on EBL phase).
Max Green = 17 seconds  
Avg Green (EBL) = 15.3s  
p (max-out) = 84.6%  
Avg bus delay = 98.4 s  

Max Green = 21 seconds  
Avg Green (EBL) = 17.8s  
p (max-out) = 51.2%  
Avg bus delay = 67.3 s  

Figure 5-2 Green Time Distribution for East Bound Left Approach Under Base Case and Passive Priority (Split Adjustment) at Ruggles-Tremont-Whittier Intersection

Since this is an actuated approach (EBL), adding 4 seconds to this left-turning approach only increased the green duration by 1.4 seconds. This 1.4 seconds increase in average EBL green duration reduced average EBL bus delay by 32.1 seconds (98.4 seconds to 67.3 seconds) and decreased the percentage of max-out by 32.1% (83.3% to 51.2%) by limiting oversaturation.

Green time distribution of EBL approach at Ruggles-Tremont-Whittier intersection under passive priority (adjusted splits) and green extension is provided in the following figure.
Simulation results indicated that green extension is granted to EBL buses 21.3% of the time and this increased average green duration by only 0.3 seconds. The probability of max-out was decreased by 26.5% (51.2% to 24.7%) once the extension is accomplished. As a result, average bus delay decreased by 12.2 seconds (67.3 seconds to 55.1 seconds with almost no impact on WBT traffic.

Green extension was also applied for SBL buses at intersection #3 to improve the coordination plan when there is a pedestrian is not present on Whittier St (Figure 4-2). Figure 5-4 displays the green time distribution for SBL stream at Ruggles-Tremont-Whittier intersection before and after green extension.
The percentage of green extension is much lower for SBL buses (only 5.1%) due to the lower bus volume, the shorter green extension increment (5 seconds) and the reduced need for a green extension (extension is generally not required resulting from good progression). There is a very small increase (0.6%) in the proportion of intermediate green times. This results from holding the signal green for buses that request priority by actuating the check-in detector at busway when the normal SB traffic on Ruggles St. (intersection #3) has already gapped-out (Figure 4-5). Consequently, SBL green duration was increased by 0.2 seconds on average when extension is applied.

Phase insertion is the last tactic that was tested at Ruggles-Tremont-Whittier. In addition to applying green extension, a “phase insertion” approach was also used for EBL buses.
Simulation results revealed that phase insertion reduced average bus delay by 22.1 seconds (55.1 seconds to 33.0 seconds) by increasing average EBL green one second (Figure 5-5). However, phase insertion has a measurable impact on WBT traffic. Average green time for WBT traffic was decreased by 2.5 seconds, where one second is due to the increase in average EBL green duration, and the rest is due to change interval loss time (yellow + all red) when an extra phase is inserted.

The following figure displays the delay results for bus approaches and WBT approach, which is mostly affected from priority interruptions at Ruggles-Treomont-Whittier intersection.
For EBL buses, dramatic reduction (65.0 seconds) in delay was obtained when priority tactics were implemented, where most of the benefit was gained from passive priority (32.1 seconds). When all priority tactics were applied, EBL bus delay was reduced by 65.0 seconds (98.4 seconds to 33.4 seconds).

For SBL and SBR buses, the majority of the reduction is similarly due to passive priority, which provides green waves and coordination for buses. SBR buses experience almost no delay, while the delay for SBL transit vehicles is still more than 10 seconds due to the poor coordination, requiring green extensions in some cycles. As a result, application of green extension for SBL buses reduced average SBL bus delay to 8 seconds. Finally, since phase insertion disrupted the bus coordination (Figure 4-12), it caused a relatively small increase in SBR and SBL bus delay (4.4 seconds and 2.9 seconds respectively).
Priority strategies except phase insertion caused negligible impacts (less than 3 seconds) on WBT traffic as expected before. However, when phase insertion was applied, WBT delay was increased by 13.3 seconds (26.8 seconds to 40.1 seconds).

The TSP tactics applied at this intersection have different impacts on the measures of effectiveness (Figure 5-7).

Simulation results revealed that average bus delay was diminished by 27.6 seconds (58.7 seconds to 31.1 seconds) with passive priority improvements. The reduction is mostly attributed to the prevention of oversaturation on EBL approach, and the implementation of a coordination plan, favoring all transit movements at intersection #3. Bus delay was further decreased to 17.7 seconds when all priority strategies were applied incrementally. However, it should be recognized that some of the strategies applied at this intersection might aggravate transit movements at downstream
intersections, and therefore origin-destination results should also be analyzed while evaluating different priority scenarios (Section 5.3).

Priority schemes including phase insertion improved the overall efficiency of the intersection, while phase insertion has a small impact on the traffic when compared to green extension. Average vehicle delay was minimized when passive priority and green extension were applied (2.5 seconds reduction). In case of phase insertion, the delay is still lower than the base case (1.6 seconds reduction), but higher than the green extension. When higher occupancy of transit is taken into account, all of the strategies reduced average person delay.

5.2.3 Tremont Street – Melnea Cass Boulevard (Intersection #5)

Green extension and phase rotation are the two strategies that were applied to reduce bus signal delays at Tremont St.–Melnea Cass Boulevard intersection (#5). Priority was tried only for the buses traveling from south direction (NBT Buses). Application of TSP includes green extension and phase rotation.

Phase rotation influences the red time distributions by changing the order of the signal phases to accommodate transit priority. The red time distributions of approaches that are affected by phase rotation at Tremont St.-Melnea Cass Boulevard intersection is shown in Figure 5-8.
Red time distribution based on the two scenarios revealed that the mean values are similar with a little higher standard deviation when rotation is permitted. Rotation decreases the red time when it follows normal phase, and increases red duration when precedes normal phase. Buses do not fall on the right side of the plot (longer red times), because they never experience normal phases followed by rotated phase. Even in the worst scenario (rotated – rotated), they are subjected to mean red time. As a result, considering the high occupancy of the buses, phase rotation decreases average person delay at this intersection.

Since rotation takes place between NBT and SBT vehicles when priority is accomplished, it has an effect on SBT traffic as well and the red time distribution for SBT stream (Figure 5-9).
Figure 5-9 Red Time Distribution for South Bound Through Phase at Tremont St.-Melnea Cass Boulevard Intersection Under Base Case and Phase Rotation

The deviation is much higher compared to NBT red time distribution (Figure 5-8), and the impact on red time is much more evident for SBT vehicles. The mean red times are almost the same; however there is a big difference (12.8 seconds) in the standard deviation. While some vehicles experience only 50 seconds of red time, it could be increased to more than 120 seconds in some cycles due to phase rotation.

On the other hand, because SBT traffic is low (only 59veh/hr, note that SBR volume was excluded in calculations since right turn on red strategy applies for those vehicles) the impact of phase rotation on SBT at this intersection is alleviated.

Including phase rotation in the signal timing plan had varying results for each approach (Figure 5-10).
Simulation results indicated that the provision of transit priority was beneficial to NBT buses. NBT bus delay was reduced by 7.8 seconds (41.5 seconds to 33.7 seconds) with no measurable impact on WBT traffic (the required green time for extensions was taken from this approach). Since the WBT approach does not carry significant traffic and the extension is granted only 5.6% of the morning peak cycles, the average delay was only increased by 0.7 seconds.

Phase rotation with green extension led to a reduction of an additional 6.8 seconds in the NBT bus delay. For the SBT traffic, however, priority interruptions increased the delay by 6.5 seconds due to an increase in red time in some cycles which was caused by phase rotation.

At this intersection, buses use 3 different approaches and priority strategies only favor NBT bus movements (main bus movements, 61.5% of the buses). Applying phase rotation at this intersection also affected other bus approaches (Figure 5–11).
Priority schemes provided for NBT buses decreased average bus delay from 39.1 seconds to 28.5 seconds, indicating that the impact on competing transit routes is not detectable. Moreover, the implementation of transit priority reduced average vehicle delay and average person delay slightly. At this intersection, the proportion of buses to the general traffic is much lower as opposed to Tremont-Ruggles Intersection. Thus, the reduction in average person delay is almost the same as average vehicle delay.

5.2.4 Melnea Cass Boulevard – Columbus Avenue (Intersection #6)

This intersection serves incoming bus routes that use the back entrance to enter the terminal. Two different bus approaches with 22 buses per hour enter this intersection during the morning peak and the priority tactics evaluated include passive priority and early green.

Using passive priority tactic, the cycle length was increased from 90 seconds to 100 seconds at this intersection to provide coordination with the upstream intersection.
Figure 5-12 Recommended Signal Timing Plan for Melnea Cass Boulevard-Columbus Avenue Intersection, Passive Priority

Offsets and split adjustments were also accomplished to facilitate the movement of NBT buses, which accounts for 72.7% of incoming bus routes (Figure 5-12).

Recommended signal timing plan indicates that the coordination plan provides good progression for NBT buses (main bus phase), whereas it does not favor WBR transit vehicles. However since it is a coordinated approach, at the upstream intersection (intersection #5), the WBR phase gets the extra time from the actuated approaches, and starts earlier due to the low volume of traffic on the SBT phase unless there is a pedestrian call. Thus in some cycles, the WBR buses could clear the downstream intersection (intersection #6) with no delay if they can use the last portion of the bus phase.

The average bus delay by intersection and by approach varies at this intersection (Figure 5-13).
Average Bus Delay
(s/veh)
Buses coming from south
(s/veh) - NBT Buses
Buses coming from east
(s/veh) - WBR Buses

Figure 5-13 Bus Delay Times at Melnea Cass Boulevard–Columbus Avenue Intersection Under Base Case, Passive Priority and Early Green

In the base case, even though the traffic volume is low, buses experience 22.4 seconds delay due to the absence of coordination and pre-timed control. Merely providing coordination for NBT buses, which accounts for 72.7% of total bus volume, reduced the average bus delay to 12.0 seconds. However, since the coordination plan only favors NBT buses, WBR bus delay was increased by almost 6 seconds.

On the other hand, early green, which provides priority for both bus approaches, reduced average transit delay to 7.1 seconds. Although this reduction is significant, some delay still exists because the time required for a pedestrian to safely cross the intersection cannot be truncated, which decreases the responsiveness of priority treatments.

This limitation arises for the NBT buses if there is a pedestrian call at intersection #6, and if the NBT phase starts earlier at intersection #5 (Figure 4-9). Consequently, while the delay for WBR buses is only 3.8 seconds, it is 8.4 seconds for NBT buses.
Simulation results indicated that having highly flexible, fully actuated controller reduced average car delay by almost 7 seconds (Figure 5-14). The fact that buses have priority over all traffic except pedestrians, and bus phase runs concurrently with the NBL phase results in lower average car delays for NBL traffic.

On the other hand, since EBT traffic has a fixed start of green with a short green interval, average car delay for this approach was increased by more than 10 seconds. However, this increase for EBT delay has minimal impact on average car delay due to its low traffic volume (85 vehicles/hour).

### 5.3 Origin – Destination Delays

Intersection delay can be used in TSP studies to measure the effectiveness of priority applications. This is an effective evaluation method when intersections are isolated, in which they operate independently, and are not affected by upstream or downstream intersections.
However, in urban traffic, intersections are generally closely spaced and their queues may spill back into upstream intersections. This causes higher delays for upstream intersections and does not accurately represent the delay that they would normally experience. Moreover, along arterials, intersections may operate under coordination strategies where vehicles arrive in platoons during certain intervals, rather than arriving independently. Therefore any improvement in one intersection can disrupt (or improve) the coordination plan, resulting in higher (or lower) average network delay. Consequently intersection delays may not reflect actual levels of service in some cases, which necessitates the usage of origin-destination delays to better understand and analyze applied priority tactics.

In the simulation model, origins-destinations were specified for every entrance and every exit, which are linked to each other in the network. Origin-destination delay of a vehicle represents the delay experienced to reach from an origin to a destination in the network, which includes more than one intersection.

Figure 5-15 shows average delay for buses getting into and out of the terminal, as well as average bus delay in the network (i.e., average bus delay that considers both incoming and outgoing buses).
Various combined priority tactics halved average bus delay, reducing the delay by 46 seconds (90 seconds to 44 seconds). Passive priority improvements account for almost 80% of this reduction. However, it would be a mistake to conclude that active priority has little incremental value, because many active priority tactics are aimed at only at specific, targeted streams of buses, so that while their benefit averaged over the entire network (as in Figure 5-15) may be small, their benefit per targeted bus can be substantial.

The net savings per targeted bus for different priority tactics was calculated to evaluate the effectiveness of active priority applications (Table 5-1). Net savings accounts for delay changes to all buses, not just those buses in the priority stream, because sometimes a tactic that helps one stream of buses can negatively impact another.
Table 5-1 Net Savings per Bus from Active Priority Applied to Incoming and Outgoing Buses

The first column shows targeted bus streams, which active priority was applied to, and the change in their average bus delay due to priority application. The second column shows other affected bus streams (i.e., non-targeted buses), and their delay change due to active priority. To illustrate, phase insertion (PI) was only applied to W-in buses, whose impact appears in the first column. However, the application of phase insertion also affected other streams, passing through intersection #3 (e.g., S-out, E-out and W-out), whose impact is shown in second column. The last column shows net change per targeted bus, which was calculated by dividing the aggregated net change in bus delays in the first two columns, by the total number of buses in the targeted streams.

Changes shown in Table 5-1 are incremental for two intersection pairs, intersections 2&3 (Ruggles/Tremont/Whittier and Ruggles/Busway) and intersections 5&6 (Tremont/Melnea Cass and Melnea Cass/Columbus). For each pair, the first active priority tactic listed uses passive priority as baseline, indicating the incremental benefit of adding either green extension (GE) or early green (EG). For the second active priority tactic listed, we show the incremental benefit on top of the first active priority tactic.
The results indicate that both green extension and early green offers substantial benefits (more than 11 seconds per targeted bus). Phase insertion offers a similar benefit to the buses in its targeted stream, but the disruptions it causes to the background coordination (passive priority) increases delay to other bus streams, so that the net savings per targeted bus is only about 4 seconds. For the buses using the back entrance (Tremont St.-Melnea Cass Boulevard and Melnea Cass Boulevard-Columbus Avenue intersections), because passive priority already favors only S-in buses, early green gives a strong benefit to E-in buses (30.9 seconds reduction), and a comparatively small benefit to S-in buses. Finally, phase rotation (PR), which was applied for S-in buses, offers only about 2 seconds of net reduction for targeted bus.

In addition to O-D bus delays, average delay for non-transit vehicles was calculated (Figure 5-16). Vehicular delay for each O-D pair is given separately under different priority schemes. All represents average car delay for those 16 different O-D pairs.
Figure 5-16 Comparison of Average Vehicular Delay Under Successive Priority Applications, Origin-Destination Pairs

In the base case (BC), the coordination plan favors through traffic (WT – ET) which results in higher delay for turning vehicles, including buses (Figure 5-16). Furthermore it can be understood that capacity enhancement and prevention of queue spillback (PP) from Ruggles to Tremont reduced average delay dramatically for the vehicles whose destination are Ruggles Street (R).
Simulation results indicated that the priority tactics except phase insertion (PI) did not cause any measurable impact on the non-transit traffic (increase in average delay is less than 5 seconds for 13 O-D pairs and overall average non-transit delay reduced by 4.4 seconds). Maintaining the coordination for the vehicles while applying transit priority and compensating non-priority after priority interruptions mitigated the impact of signal priority.

5.4 Sensitivity to Traffic Volumes

Simulation results indicated that developed priority tactics are very effective in reducing transit delay with A.M. peak traffic volumes. In order to test the robustness of applied priority tactics with higher traffic volumes, non-transit volumes were scaled up by 10% throughout the network without any increase in bus frequencies.

Figure 5-17 shows average bus delays for incoming and outgoing bus routes with 10% increase in car volumes.

Figure 5-17 Average Bus Delay for Incoming and Outgoing Bus Routes Under Base Case, Passive Priority, and Active Priority (Non-Transit Volume Scaled up by 10%)
Based on the simulation results, the transit priority tactics work even more effectively when intersections operate closer to capacity by reducing the incidence of buses having to wait for a second cycle, or otherwise being caught in a long queue. Similar to the previous findings, most of the reduction in average bus delay is attributed to passive priority, but active priority tactics also deliver significant benefit.

Finally, average car delay is provided in Figure 5-18 to measure the impact of TSP when 10% increase in car volume was accomplished (Figure 5-16 for O-D pairs).

![Figure 5-18 Comparison of Average Vehicular Delay Under Successive Priority Applications, Origin-Destination Pairs (Non-Transit Volume Scaled up by 10%)](image)

On average, passive priority helps general traffic, by improving coordination and by preventing queue spillback on Ruggles St. Most of the active priority techniques (excluding phase insertion) have no measurable impact on general traffic (Increase in
average vehicular delay is less than 5 seconds except for the vehicles going from Ruggles St. to West Tremont St. The only exception is phase insertion, which caused significant impact on vehicles going from Melnea Cass Boulevard to West Tremont St. (MC-WT) and vehicles going from Melnea Cass Boulevard to Ruggles St. (MC-R), indicating the need for queue spillback prevention tactics as described in Section 4.15.
Chapter 6: Summary and Conclusions

Giving priority to transit vehicles at traffic signals is a traffic management strategy to reduce transit delay, transit operating cost, passenger waiting time at transit stops and to improve transit service quality. Several priority implementations proved that TSP is very effective in reducing transit delay and improving transit service. However, none of these implementations include giving priority to transit vehicles near a terminal due to the challenges of the problem.

Two cities in Europe with a good reputation of TSP underscore the challenge of giving signal priority near a terminal. While Zurich’s trams experience nearly zero delay at most signalized intersections [29], there is no signal priority near the terminal. In Eindhoven, signal priority results in nearly zero delay for late buses at most intersections; however no priority is applied where buses turn into and out of the central station [13].

The main goal of this study was to determine to what extent signal priority at the intersections around a major terminal could reduce bus delays, without disrupting the general flow of traffic.

Data were collected and a network was created using a microsimulation model (VISSIM) and simulated for morning-peak. Calibration and validation of the simulation model were performed to achieve reasonable correspondence between field data and the model output. Logic for various priority schemes was programmed using VISSIM’s optional add-on module VAP, which allows users to define their own signal control logic.

This chapter presents conclusions and summary of the findings as well as the directions for future research based on the limitations of our study.
6.1 Major Findings and Conclusions

The following findings and conclusions were obtained from field analysis and simulation results. Those conclusions can be used as guidance in providing efficient priority tactics that help improve bus movements at intersections around a major terminal while minimizing the impact on non-priority traffic.

1. Near major bus terminals, bus volume may be so high that it is not feasible to interrupt the signal cycle for every bus. Moreover, buses use different transit routes, resulting in conflicting priority requests. Therefore, around a major bus terminal, the general objective should be to minimize initial bus delay at the first intersection (e.g., the intersection that buses use to leave the terminal), and then to provide green waves for streams of buses through multiple intersections.

2. At the intersections around a major terminal, buses are likely to use minor turning phases to get into or out of the terminal. Existing signal timing plans are likely to favor through movements on arterials, not the buses turning into or out of the terminal. The challenge is to create a coordination plan offering progression to the minor movements made by buses, while still maintaining coordination for the arterial to prevent queue spillback and to avoid gridlock.

3. Oversaturation or near saturation on the minor phases used by buses result in cycle overflows that cause excessive delays for turning vehicles, including buses. Actuation with sufficiently long maximum green time to protect those phases against overflow most of the time is an effective strategy for reducing bus delay without a large impact to competing phases. Actuation protects against wasting of green time, and includes a natural compensation mechanism, because longer
greens in one cycle, by virtue of serving more cars, lead to shorter greens in the next cycle.

4. With actuated-coordinated operation, coordinating secondary phases such as left turn phases can be difficult when there is high variation in the starting time of related phases at adjacent intersections. This variation can be reduced by preventing phase skipping and/or by recalling pedestrian phases.

5. Changes to splits, offsets, phase sequences, and actuation parameters (e.g., maximum green times, described in items 2-4) can be considered passive priority improvements, because they do not involve selective bus detection. In this study, a large reduction in transit delay (14.5 seconds/bus/intersection) can be obtained with no detectable impact on general traffic using passive priority improvements, especially at the intersections with high bus volumes. From a practical point of view, those passive priority tactics can be implemented with existing signal control equipment.

6. Active priority tactics can supplement passive priority strategies in specific cases to either reduce initial bus delay, or give buses a just-in-time green wave, where interruptions will not unduly affect overall coordination or capacity. In this study, applications of green extension, early green, and phase insertion proved effective at reducing bus delay with no adverse impact on general traffic. Applications of green extension and early green yielded more than 10 seconds of net saving per targeted bus, and phase insertion reduced average delay about 4.5 seconds per targeted bus. However, dynamic phase rotation proved to offer little benefit to
buses (about 2 seconds per targeted bus), helping some buses while increasing traffic delay for some movements.

For implementation purposes, green extension can be applied with existing signal controllers by adding detection equipment. However, other active priority tactics require more advanced logic than what is found in standard.

7. Dynamic coordination, in which the start of green for a bus phase at the upstream intersection becomes a priority request at the next intersection, can improve bus coordination and is a promising strategy for other sides.

8. Developing flexible and highly interruptible control logic with compensation strategies allows implementation of aggressive priority tactics, helping reduce bus signal delay considerably without a large impact on general traffic.

9. A new tactic, cycle constrained full actuation, was developed and applied in this study at the back entrance. The main goal was to create highly flexible and interruptible signal control, which can accommodate transit priority for two different bus approaches arriving in different parts of the cycle. Queue spillback was also prevented by maintaining signal coordination for the main movement with the application of this tactic. Simulation results indicated that using cycle constrained full actuation tactic, the two actuated phases allowed to cycle freely were realized on average about two times per cycle, and sometimes were realized three times. Average delay for general traffic fell by 7 seconds, and average delay for buses fell by 13.5 seconds.

10. Passive priority improvements developed in this thesis can be considered as a pilot study to reduce both transit and non-transit vehicle delay at signalized
intersections not only in Boston, but also in the United States. The fact that there exists substantial amount of signalized intersections with outdated and poorly designed signal timing plans, implementation of passive priority might bring impressive benefits with almost zero cost, because passive priority does not require the hardware and software investment of active priority treatments since it does not require a transit detection / priority request generation system. A study conducted by Institute of Transportation Engineers (ITE) revealed that retiming traffic signals in the United States reduced average delay significantly (10 percent to 40 percent reduction in average delay) [28]

6.2 Directions for Future Research

In the last part of this thesis, the directions for future research are given in the general context of transit signal priority. Then more specifically, based on the limitations of our model, directions for priority applications at the intersections near a major bus terminal are presented.

To begin with, the scope of future transit signal priority studies can be outlined as follows:

- Typical transit detection systems are quite simple, not allowing one to detect the transit vehicles further in advance. With the enhancements in the detection methods, transit vehicles being equipped with GPS systems, early detection of transit could be achieved and advanced prediction models could be developed. This advancement allows signal controller to have enough time to modify the signal timing plan in order to accommodate priority without causing a measurable impact on general traffic.
➢ Signal controllers under fixed-time coordination strategy create rigid control and complicate transit signal priority application, especially at intersections with a large number of buses. More flexible signal controllers, responding quickly to priority requests, and recovering easily from priority interruptions, can be developed in order to facilitate the implementation of transit signal priority, and to minimize the impact on general traffic.

➢ Adaptive signal operation has been in use for many years in traffic engineering projects. The main goal of adaptive control strategy is to minimize traffic delay by continuously modifying cycle length, splits and offsets based on the real-time traffic data. Adaptive systems can be improved for transit vehicles by integrating transit signal priority within the system to accommodate priority while still having the objective of minimizing traffic delay.

Although this research was conducted with the goal of ensuring that the model represented real world conditions, there are some limitations. The limitations of our model and recommendations for future work can be given as follows:

- In this study, the intersections around Ruggles Bus Terminal were only analyzed during the morning peak and transit priority tactics were tested based on A.M. traffic. However the traffic flow pattern, such as directional flow or traffic volume, for P.M. period can be different, which can make the applications of transit priority more difficult. Thus, P.M. peak should also be studied in order to measure the range of impact on non-transit vehicles.

- Due to the location of the study area, namely near a major bus terminal, no transit stops exist in the real world, and as a result were not included in the simulation
model. Since there are no stops near the terminal, application of TSP was relatively easy. Similar analysis should be conducted in an area, having high bus volumes and transit stops in order to evaluate the effectiveness of priority strategies.

- Throughout the study, the average bus occupancy for both incoming and outgoing bus routes is assumed to be 20. In the simulation model, at the intersections where priority requests conflict (i.e., buses arrive at an intersection from conflicting directions), priority was given to an approach with the highest number of buses. However, this does not guarantee that the approach with the highest number of riders is prioritized since the number of riders on other bus approach (the one with less number of buses) may be significant. Therefore, future research should include a more appropriate tactic which would reflect the actual number of bus passengers.
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