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ASSESS IMPACTS AND BENEFITS OF TRAFFIC SIGNAL PRIORITY FOR BUSES

FINAL REPORT

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16. Abstract

Bus transportation has traditionally served as the backbone of public transportation. Despite the importance and efficiency of buses, compared to the automobile, these vehicles are weighted equally with automobiles at traffic signals where a bus carrying 50 passengers is treated the same as an auto with a single person. Delays caused by traffic signals and by street traffic congestion increase bus operating costs and degrade transit service quality. One approach to minimizing delays to bus transportation is by implementing bus signal priority. Bus signal priority is an attempt to minimize or eliminate delays to buses at a signalized intersection by temporarily altering the traffic signal phase so that an approaching bus receives a green phase when it arrives. The potential savings in bus travel times can allow buses to maintain its schedule and provide better reliability in travel times.

Although signal priority has proven to be an effective tool for reducing delays to buses, this technique is not always beneficial to the overall traffic network. Providing priority for transit vehicles along a corridor with a large number of transit vehicles can cause a coordinated network to be out of step resulting in an overall increase in delay. Bus signal priority also has the disadvantage of penalizing the cross-street traffic when high transit volumes exist at the corridor. The objectives of the research described in this report is to assess the impacts of and the implementation issues associated with the use of bus signal priority in New Jersey and to assess the benefit and costs of signal priority.

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EXECUTIVE SUMMARY

Delays caused by traffic signals and by street traffic congestion increase bus operating costs and degrade transit service quality. One approach to minimizing delays to bus transportation is by implementing bus signal priority. Bus signal priority is an attempt to minimize or eliminate delays to buses at a signalized intersection by temporarily altering the traffic signal phase so that an approaching bus receives a green phase when it arrives. The potential savings in bus travel times can allow buses to maintain its schedule and provide better reliability in travel times.

Although signal priority has proven to be an effective tool for reducing delays to buses, this technique is not always beneficial to the overall traffic network. The objectives of the research described in this report is to assess the impacts of and the implementation issues associated with the use of bus signal priority in New Jersey and to assess the benefit and costs of signal priority.

To assess the benefits and costs associated with implementing signal priority, a simulation study was performed of Broad Street in Newark, New Jersey. Broad Street was selected based on the recognized transit corridor on the roadway, the roadway and bus passenger volumes that suggested that priority may be warranted, and the availability of data. The study area included 15 signalized intersections and 2 unsignalized intersections on the primary arterial, and 8 signalized intersections on two of the major cross-streets.

The effects of implementing bus signal priority on the operation of transit and non-transit vehicles along Broad Street were examined for AM and PM peak hours with existing and future (+10% and +20% traffic growth) traffic volumes. The study found a beneficial impact on both transit and other arterial traffic when transit priority was introduced. There was an expected increase in both bus and auto travel times (relative to the original base) when traffic grows by 10%, without any transit priority. At the same time, there were adverse impacts to the cross streets of Raymond Blvd. and Market Street. However, improvements due to signalization changes equal or exceed those due to transit priority operating with the existing signal timing. As a result of bus travel time reductions, the number of buses servicing the route was determined to be reduced to 9 by slight adjustments to the schedule. The important underlying principle is that for some combinations of these factors ---- notably longer routes, higher bus frequencies, lower bus speeds, and material savings in travel time due to bus priority --- there is an important potential for reducing the number of buses needed to service a route and to reduce operating costs.

From the research recommended guidelines were developed for identifying locations where bus signal priority would have the greatest benefits. Bus signal priority should be considered at locations where a significant portion of the bus delay is at signalized intersections; where bus stops are located at the far-side of the intersection;

where bus volumes are between 10 and 20 buses during the peak hour; for express bus service routes, where all vehicles queuing at signalized intersections discharge in one cycle; where the level-of-Service for the cross-streets is D or better; where bunching of buses at bus stop does not occur, where pedestrian volumes are low to moderate; and where AVL technology exists or is planned.

The research demonstrates that bus signal priority can be effective in New Jersey with significant benefits associated with this treatment. The research also demonstrates that bus signal priority may not be appropriate at heavily congested locations or locations serviced by local buses with frequent stops. A successful implementation of signal priority warrant careful consideration of not only the transit impacts, but the vehicular impacts. Simulation has proved to be a necessary first step in determining the appropriateness of implementing a bus signal priority treatment on an arterial. Although general guidelines can be provided on where signal priority may be effective, each location warrants a separate analysis, similar to the type of analyses performed in this research.

INTRODUCTION

Overview

Bus transportation has traditionally served as the backbone of public transportation. Despite the importance and efficiency of buses, compared to the automobile, these vehicles are weighted equally with automobiles at traffic signals where a bus carrying 50 passengers is treated the same as an auto with a single person. Delays caused by traffic signals and by street traffic congestion increase bus operating costs and degrade transit service quality. Reducing transit travel times, improving schedule adherence, and increasing passenger comfort can work toward increasing bus ridership. Moreover, reducing delay for transit vehicles, whether along a specific corridor or on a network-wide basis, allows the transit agency to operate more efficiently, thereby reducing overall transit system operating cost.

One approach to minimizing delays to bus transportation is by implementing bus signal priority. Bus signal priority is an attempt to minimize or eliminate delays to buses at a signalized intersection by temporarily altering the traffic signal phase so that an approaching bus receives a green phase when it arrives. The potential savings in bus travel times can allow buses to maintain its schedule and provide better reliability in travel times. This may attract additional riders away from automobiles to transit. Signal priority differs from signal preemption, as used at at-grade railroad crossings or for emergency vehicles, where unconditional priority is provided to all approaching vehicles equipped with detection technologies. Signal priority provides conditional priority dependent on various objectives of the transit system authority. Some of these objectives may be to reduce vehicular emissions, reduce transit operating costs, reduce vehicle and person delay, to name a few (TCRP, 1996).

Although signal priority has proven to be an effective tool for reducing delays to buses, this technique is not always beneficial to the overall traffic network. Providing priority for transit vehicles along a corridor with a large number of transit vehicles can cause a coordinated network to be out of step resulting in an overall increase in delay. Bus signal priority also has the disadvantage of penalizing the cross-street traffic when high transit volumes exist at the corridor. This can create significant delays at locations where the cross-street carries significant traffic volumes. Some traffic engineers, local elected officials, and others have been reluctant to provide traffic signal priority for transit out of a concern that it would cause non-transit vehicles to encounter significantly increased delay.

Research Objectives

The objectives of the work performed under Task Order NCTIP-45, Project 2001-28, Assess Impacts and Benefits of Traffic Signal Priority for Busses were to:

- To assess the impacts of and the implementation issues associated with the use of bus signal priority in New Jersey;
- To develop operational test plans for implementing signal priority at promising locations; and
- To assess the benefit and costs of signal priority.

The tasks performed to achieve these objectives include:

Task A. Conduct a literature search of the current state of the practice.

Task 1. Develop a list of locations where traffic signal priority systems have been installed and collect information on the impacts and implementation issues encountered and overcome by these agencies.

Task 2. Work with NJ Transit to identify promising locations and develop an operational test plan for implementing signal priority at these locations.

Task 3. Develop operational test plans to assess the benefit and costs of signal priority.

Task 4. Prepare quarterly progress and final report with appropriate tables, graphs and chart. Deliver final report in hard copy version, pdf file version for use on NJDOT web site, Word97, and on CD ROM.

Organization

This report is organized into six chapters. The Introduction chapter introduces the problem statement and the objectives of the research. The Literature Review provides a comprehensive and critical review of studies in the USA and other countries that have looked at transit signal priority systems. Potential Locations for Implementation describes the selection criteria used for identifying promising sites for implementing signal priority. Using this criteria, sites found to have promise will be discussed. The Simulation Study describes the simulation model and approach used to assess the benefits and determine the operational impacts of signal priority. Operational test plans for implementing signal priority at locations with promise are provided. Details of the strategy, hardware, and operational conditions will be provided. Finally, the final chapter provides a summary of the study, including the conclusions and recommendations.

LITERATURE REVIEW

Overview

A comprehensive and critical review of signal priority studies in the US and abroad was performed to evaluate the effectiveness of signal priority strategies and algorithms previously used. One of the objectives of the literature review was to obtain information on the impact of transit signal priority on delay to transit vehicles, schedule adherence, cross street traffic, pedestrians, overall delay, and accidents. Information on the criteria used to select the bus routes for implementing signal priority was also investigated. A second objective of the literature review was to gather information on the costs, hardware and software used for implementing signal priority. The choice of hardware and why a particular technology was selected for field implementation was also investigated[1]. Finally, information addressing "non-technical" issues, such as the political, economic, and legal issues associated with implementing signal priority were investigated. Implementation issues can be of even greater importance than some of the more technical issues. As an example, there is sometimes a perception among elected officials and the public that transit signal priority may not be beneficial for all road users. In addition, depending on the routes and the network under consideration, it may be necessary for several jurisdictions to be involved in the project. The implementation issues reviewed sought to identify ways of addressing these 'non-technical' issues. Due to the lack of published reports and papers, agencies implementing priority systems were contacted to understand how these issues were addressed.

Background

On-street transit service can be significantly delayed by traffic congestion and traffic signals. Traffic signal priority (TSP) can reduce the time that transit vehicles spend delayed at intersections, and therefore, reduce delay, improve transit service reliability, and improve the quality of transit service. Although TSP was discussed as early as 1962[1], recent developments in the field of Intelligent Transportation Systems (ITS) have facilitated the growth of TSP [2].

Sometimes TSP is confused with signal preemption. It is important to understand that TSP and signal preemption are different systems. With preemption, the normal process is interrupted to respond to special events, e.g., emergency vehicles, where the traffic signal timings are abruptly changed to allow the vehicle to pass

[1] A recent paper by Hu et al. (2001), provides some information about hardware that was evaluated by LA DOT for vehicle detection. Three different technologies were considered: infra-red beacon system, loop transponder detection system (LTD), and radio-frequency antenna-transponder detection system. The LTD was selected because of ease of installation, and lower capital and maintenance cots. Other studies have mentioned the use of GPS for vehicle identification.

through the intersection. In TSP, the signal system is modified to accommodate transit vehicles [3].

The primary objective of signal priority is to provide priority service to transit vehicles without significantly affecting other vehicles on the roadway. Signal priority can also be used to improve schedule adherence for transit vehicles. In some cases, delays to transit vehicles can be so significantly reduced, that the same service could be provided with fewer transit vehicles. In addition, since transit vehicles carry more passengers than automobiles, signal priority can lead to more efficient movement of people.

Priority Concepts

Three types of priority can be provided: passive priority, active priority, and real-time. With passive priority, the traffic signal is adjusted to the bus schedule using a combination of fixed-time and schedule-based control strategies[1]. One example of passive priority is to time the signals to progress vehicles through adjacent traffic signals to assist the transit vehicle. Passive priority techniques can be efficient when transit operations are predictable (e.g., consistent dwell times), transit frequencies are high, and traffic volumes are low [3]. Very few applications of passive priority can be found in practice.

With active priority, signals are changed as each bus is detected as it approaches an intersection. Active priority strategies can include: early phase activation, phase extension, special transit phase (queue jump), phase suppression (lift strategy), unconditional priority, and conditional priority [3]. In early phase activation, or *early green* strategy (same as *red truncation* strategy), the movement where the transit vehicle is detected receives an expedited return to green. This strategy is only used when the signal is red for the approaching transit vehicle [3]. Similarly, phase extension typically deals with a *green extension* strategy, where the green time for the transit vehicle is extended when the transit vehicle is detected.

Another active priority technique is to introduce a special transit phase (queue jump). Using this approach, the transit vehicle would be allowed to enter the downstream link ahead of the normal traffic stream [3]. In some cases, the order of signal phases can also be 'rotated' (i.e., *phase rotation*) to provide priority to the transit vehicle. As an example, a northbound left turning bus arriving before the start of the green phase could be given the green although in the normal phase plan, the northbound left turn receives the green after the through movement. With phase rotation, the phase serving the bus could be provided green first to expedite the passage of the transit vehicle. With phase suppression, phases with low demand may be omitted from the normal phase sequence[1].

Unconditional priority is given whenever a bus detector requests it from signals[1]. This strategy may not be appropriate in many circumstances. With conditional priority, priority is provided depending on the value of certain variables and conditions, such as, occupancy of the bus, traffic conditions including queue length, and whether the bus is behind schedule.

TSP strategies provide priority based on trying to optimize some performance criteria[2]. The criteria may include person delay, transit delay, vehicle delay, and/or a combination of these criteria. Real-time strategies make use of pedestrian and traffic volume data as input to traffic models that determine an effective timing plan that will optimize the selected performance criteria. For real-time strategies to work, early detection of transit vehicles is essential.

In this context, another concept that is of interest is *signal recovery / compensation* [3,1]. With this concept, signal phases that were truncated or cut short during the priority event are compensated to make up for lost time.

Implementing Transit Signal Priority

Transit Signal Priority (TSP) has been more popular in Europe. Reluctance to implement these systems in North America, is based on several reasons including[3]:

- Lack of broad awareness of the technical feasibility and cost-benefit;
- Lack of proven, accurate, reliable and cost-effective detection products;
- Limited installations of vehicle location systems by transit properties;
- Absence of standards;
- Traffic signal controllers did not have the capability to support TSP;
- Traffic signal controller software did not have the ability to support TSP;
- Costs associated with deploying and maintaining traffic signal controllers, transit vehicle, and TSP was cost prohibitive; and
- Institutional, planning and partnering issues between the transit properties and the local transportation departments (who often operate the traffic control signals).

Over the past few years, however, there is growing momentum to implement TSP. According to a survey conducted by the Canadian Urban Transit Association (CUTA) in December 1999, of all transit providers in North American operating over 100 vehicles, 54.7% responded that they have TSP projects in the planning stage[3].

Planning a TSP project can be a complicated venture, and several issues need to be considered. First, it would be useful to identify the stakeholders. Once the stakeholders are identified, there should be a process where they can meet periodically to make decisions regarding:

1. TSP strategies
2. Technologies
3. Corridors where TSP will be implemented
4. How the system will be maintained?
5. How TSP will be evaluated?

Priority System Components

With regard to equipment, there are potentially five elements that should be purchased or modified for the transit priority system. These elements include: (1)the intersection equipment; (2)the bus equipment; (3) the communication system between the vehicle and intersection equipment; (4) the central traffic signal management system; and (5) the transit management system. The first two elements are essential for operating the transit priority system. The last three elements are optional and usually depend on characteristics of the existing systems [3].

Priority Request System

There are generally two different approaches to providing TSP: local intersection level and network level[3]. With TSP at the local intersection level, the approach transit vehicle is detected upstream and information is sent to the traffic signal controller. The request for transit priority is granted using either early green (red truncation) or extension of the green strategy, depending on some user defined criteria. It is imperative that such red truncations respect any minimum green times governed by pedestrian crossing constraints that are in effect.

Network level approach is more sophisticated and would require automated vehicle location technologies, which can determine if the transit vehicle is behind schedule before communicating to the traffic signal controller that priority is requested[(4,5)].

Detection System

The detection and priority request system may depend on whether a local intersection level approach is being used or a network level approach is being used[3]. Local level detection can be accomplished with an on-board transmitter in the vehicle and a receiver at the intersection approach. For detection at the network level, a transit vehicle may communicate with a transit or traffic management center, providing its location directly.

Detection systems can include induction loop detectors, conventional induction loop detectors, optical emitters, radar detectors, video detectors, GPS/AVL, and Radio Frequency (RF) tags, depending on whether the transit vehicle has an exclusive right of way or it shares the right of way with other vehicles[3]. In the latter case, the detection system should be able to distinguish between transit vehicles and other vehicles.

Drivers can request priority as in a *driver activated* detection system[3]. This system was used in the UTCS/BPS project in Washington, D.C., during the 1970's. It was found that "drivers tended to turn the transmitters on and leave them on even when priority was not needed". In addition, it could be argued that, "manually activating the system increases the driver workload during the most critical parts of their operation, approaching and leaving the transit stop, which raises safety concerns".

Detection systems can be point detectors, area detectors, zone detectors, and exit detectors[3]. *Point detectors* are "somewhat limited since they do not provide information about the transit vehicle between detection points". If point detectors are going to be used, it may be better to utilize multiple point detectors.

Area detectors, such as GPS/AVL, are able to monitor a vehicle's movement through an area[4]. With area detectors, it is much easier to predict the arrival of the transit vehicle at an intersection.

Zone detectors, in some ways are similar to point detectors, and can provide information that a vehicle is somewhere on the approach within 500 feet for example, and is requesting priority[3]. Many TSP systems include *exit detection* systems that can "detect when the transit vehicle exits the signalized intersection", and can provide a more efficient traffic operations.

Communications Systems

An effective communications system is key to the success of TSP. The communications system for TSP is responsible for the transfer of information between the vehicle, local intersection, traffic management, and a transit management center, depending on the type of TSP that is in place. Examples of technologies include radio systems, cellular data (CDPD), dedicated short-range communications (DSRC), Optical, and infra-red (IR) [3].

Traffic Signal Control System

The traffic signal control system obtains information about the priority request, decides if priority should be granted, and make appropriate changes to the signal timings via the local traffic signal controller[3]. The decision to provide (or not provide) priority could be decided at the local intersection level or by a central traffic signal control system.

Traffic signal control at the intersection level falls into one of three categories, (1) fixed time, (2) actuated (free and coordinated), and (3) adaptive/real time. Fixed time signals use "fixed" signal timing parameters, such as cycle length, phase sequence, and an green time for each movement during every cycle regardless of the demand for the movements. Actuated signal control, on the other hand, can collected data on the current demand for the movement to allocate green time on a phase-by-phase basis. Real-time adaptive signal control systems monitor traffic conditions and implement appropriate signal timings that best serves the current traffic needs[3].

Benefits and Costs

Benefits

It has been estimated that transit vehicles spend between 8 and 15% of their time waiting at traffic signals [3,6]. Hence, as discussed earlier, an effective TSP can reduce transit travel times, improve transit schedule reliability, and make transit more attractive. In addition, it could be argued that reduced stops can lead to reduced wear and tear on equipment, less pavement maintenance, increased rider comfort, and reduced emissions[3].

The magnitude of the benefits associated with signal priority will depend on the type of system that is implemented and the traffic conditions in the area. Differences in the conditions (e.g., traffic volume changes, incidents, weather, holidays) before and after implementation of TSP can affect the results. In addition, in some cases, TSP is implemented with other transit preferential treatments such as exclusive transit lanes, and it may be difficult to isolate the effect of the TSP. In order to predict the possible changes that may result from the implementation of TSP, simulation has been used.

Field Study Results

Results are available from field implementations and simulation studies conducted in North America, and are summarized below (more detail about selected studies are presented in Appendix I). Overall, results of field studies show some benefits due to signal priority. In some cases, TSP was associated with an increase in delay for cross street traffic.

Los Angeles – Several changes were made to the transit system including, low floor buses, signal priority, and a reduction in the number of stops. Overall benefits from all changes: a 20-27% reduction in travel time. Benefit due to signal priority estimated (subjectively) to be 30 to 40% of this reduction. The adverse impacts on cross street traffic were minimal [7, 1].

Seattle – Rainier Avenue – Intersection bus delay reduced by approximately 5 seconds per TSP – equipped intersection. In addition, intersection bus delay was reduced by an average of 34 % when a bus was eligible for priority treatment [1].

Seattle – Intersection of Rainier Avenue and Genesse Street – A 50% reduction of signal related stops by prioritized buses. A 13.5% decrease in intersection average person delay [1].

Portland – There was a 5 to 8% reduction in travel time [8]. Overall effect of TSP on traffic was not very clear.

Toronto – There was 15 to 49% reduction transit signal delay for street cars. 1 street car was removed from service [3].

Chicago – There was a 6 to 20 percent reduction in transit travel time. Transit schedule reliability improved. However, there was an 8.2 second average increase in cross-street stop delay [9,3].

San Francisco – There was a 6 to 25% reduction in transit signal delay [3,10].

Minneapolis – There was 0 to 38% reduction in bus travel times depending on TSP strategy. However, there was an overall increase in traffic delay of 23%. In addition, skipping of signal phases was found to cause some confusion among drivers [3].

Simulation Study Results

Ann Arbor, MI – NETSIM was used to assess the effect of providing signal priority on the Washtenaw Avenue Corridor in Ann Arbor, MI. Bus travel time and delay were reduced when an optimal bus priority strategy was used. However, signal priority was found to disrupt traffic progression and increase overall delay [11].

Shoreline, WA – VISSIM was used to study the effect of four alternative transit and roadway improvements intended to provide priority to transit [12]. TSP was included in all the four alternatives, and hence, its individual effect could not be determined.

Tucson, AZ – CORSIM was used to assess the effect of bus priority [4]. Bus priority led to a reduction in travel time for busses. However, average intersection delay increased in the cross streets increased.

Costs

A very limited amount of information is available regarding costs of transit systems [3]. In general, the cost associated with implementing signal priority is reported in terms of average dollars per intersection. Cost data, however, may be available from different sources and are not always comparable. In one case cost data may include only roadside equipment. In another, costs to equip buses are the primary costs used in determining overall costs for the system. Additionally, depending on the type of system used, some systems are more expensive in terms of roadside equipment, while others use more expensive on-board equipment. Chang [3] argues that the following can affect cost of a TSP system:

- Design and desired functionality of TSP system
- Type of roadside and on-board equipment
- Developing new equipment vs. use of off-the-shelf equipment
- Upgrading signal controller firmware to provide TSP
- Operations and maintenance of equipment
- Training personnel in how to program/use TSP equipment
- Trenching required to access power and to place in-road detection equipment
- Ease of installing on-board equipment
- Pilot studies and before/after studies
- Time needed to establish interagency relationships and form agreements

Available data indicates that costs for implementing signal priority can vary between $8,000 and $35,000 per intersection [3].

Very few studies have conducted an economic analysis of the costs and benefits of traffic signal preemption for busses. Khasnabis et al.[13] computed a benefit-cost ratio, defined as the ratio of the benefit (net savings in delays, fuel savings, and emissions) to the annual cost (equipment, maintenance, and operation). Person delays were the focus of this evaluation instead of vehicle delays. The study concluded, that in this particular situation, preemption can be justified only by means of savings in delay, and neither the savings in fuel nor the changes resulting from increased emissions is likely to affect the economic consequence of preemption.

Stakeholders

The stakeholders will typically include transit agencies and traffic engineers that are responsible for traffic signal operations. However, it is important to include other agencies whose operations are also affected, e.g., emergency services, metropolitan planning organizations, federal agencies, public officials, and the general public. Following is a discussion about the individual stakeholders [3]:

Transit Agencies: Transit agencies typically champion the development of a TSP system.

Traffic Engineering / Signal Systems Operators: Traffic Engineers play an important role in different stages of planning and implementing a TSP system. It is important that they are included in the process from the beginning, and their concerns addressed. For example, Gifford et al. [14] in their survey found that traffic agency representatives are concerned that buses with low occupancy will get priority.

It is important that transit agencies and signal system operators communicate from the beginning. Both should be aware of each others' goals, objectives, and the technologies available.

Emergency Service Providers: In many areas, emergency service providers use preemption systems to expedite their response to incidents. It may be possible to integrate these preemptions systems with TSP systems, and reduce costs. Again, they need to be involved in the process from the beginning so that their concerns and questions are addressed. Gifford[14] in their survey found that some emergency personnel are concerned that TSP may disrupt the operation of the preemption system or the granting of preemption to emergency vehicles.

Metropolitan Planning Organization (MPO): It is well known that MPOs exercise significant control over funding of transportation projects. By involving them early in the process, their support would be easier to obtain.

Federal Agencies: Federal agencies (e.g., Federal Transit Administration-FTA and Federal Highway Administration-FHWA) are important in many ways:

(1) They may be familiar with other TSP projects in the country and could provide valuable advice on the advantages and disadvantages of alternative approaches.

(2) They would be familiar with funding opportunities at the federal level that local agencies could utilize.

(3) They can help to ensure that the system is compatible with the existing architecture and standards.

Public Officials: Elected officials do control at least a portion of the funding of projects and should be involved in the process. They also typically may have some opinions based on the feedback that they may have received from the general public. For example, Gifford [14], in their survey of elected officials found the following opinions:

- Primary objective should be schedule adherence
- Not clear if benefits would outweigh costs

- Concern that priority would disrupt traffic and worsen congestion and delay – need for local field tests to show traffic conditions improved or at least became no worse.
- Overall coordination of traffic signals across jurisdictions would have a greater impact on on-time performance of buses.
- Some were concerned about backlash from motorists who might raise ‘tax-equity’ issues.

Public: There should be avenues for the general public to be involved in the process. Information could be presented in a website. Periodic town meetings during different stages of the process could also useful.

TSP Design / Implementation Issues

There are many factors that affect the implementation of a TSP system. Some of these factors are discussed below [3]:

Roadway geometry: Roadway geometry including number of lanes and the spacing between intersections is an important factor that will affect the design of the TSP.

Peak vs. non-peak: In most urban areas, there is a significant difference between peak and non-peak hours in terms of traffic volumes. It is possible, that different strategies may be required at these two different time periods.

Signal controllers: There are generally three types of signal controllers available today: (1) NEMA, (2) Type 170, and (3) Advanced Transportation Controllers (ATC) (such as Type 2070). In general, the most common form of TSP implemented by the first two types of controllers is an early green/green extension for TSP-equipped vehicles. ATC controllers are relatively new and provide the greater computing power that may be necessary for more advanced types of TSP (e.g., adaptive/real-time systems that predict transit’s arrival time and adjust the signal time to facilitate the passage of the transit vehicle while attempting to minimize traffic impacts).

Delay parameters: It is generally accepted that the objective should be to minimize total person delay instead of total vehicle delay, and the algorithms and strategies should be designed with this objective in mind.

Pedestrian issues: As mentioned earlier, in most instances, the time required for a pedestrian to safely cross the street at a signalized intersection may limit the amount of time available for TSP.

Adjacent intersection/corridor operations (e.g., cross-street progression) need to be considered when implementing TSP.

Mixed vs. exclusive right of way: Schedules for busses that operate on exclusive right of way are easier to control and will affect the type of TSP that is implemented.

Location of bus stops: “If the transit vehicle is detected upstream from a near-side stop, the dwell time at the stop needs to be considered in the TSP timings. It is important to consider the trade-offs between passenger benefits of near side stops and benefits of signal priority”.

POTENTIAL LOCATIONS FOR IMPLEMENTATION

Overview

One of the objectives of this research is to develop operational test plans for use in implementing signal priority in New Jersey. To ensure that signal priority is targeted for suitable locations so that future evaluations will correctly assess the benefits of signal priority rather than the appropriateness of the site for signal priority, a selection criterion for identifying potential locations for implementation was developed. The criterion is based on literature sources providing information on factors that should be considered before implementing signal priority. A review of successful deployments of signal priority was also reviewed to determine additional factors needed at locations where signal priority is to be implemented. These factors, and their impacts on the effectiveness of signal priority, were used to develop guidelines for which promising sites for implementing signal priority will be identified. This Chapter provides a discussion of the selection criteria used to identify promising sites for implementing signal priority and a description of the sites identified.

Selection Criteria Factors

The selection criteria for identifying locations where signal priority would be appropriated is based on both quantitative and qualitative conditions that either impede or are beneficial to signal priority. The overall benefit or effectiveness of transit priority is a function of several factors related to the geometric configuration, traffic conditions, and transit service where the transit priority scheme will be implemented. Skabardonis(15) identified some of these factors as shown in Table 1. The following provides some discussion on some of these factors, stating the overall impact of the factor on successfully implementing a transit priority system.

<u>Bus Volumes</u>

Bus volumes impact the number of priority calls that are placed on the arterial. Too few buses may make the investment in the priority system questionable. At locations with heavy bus volumes, the large number of priority calls may result in improved operations for all vehicles on the arterial. This improved condition, however, comes at the expense of increasing delays to vehicles on the cross-streets or to movements not served by the transit vehicle. An upper limit exists for the number of buses that can be served by the transit priority system. This limit is a function of the cross-street volume.

Table 1. Transit Priority Factors

Category	Transit Priority Factors

Network Configuration and Characteristics	• Roadway network
	  ○ Single arterial
	  ○ Grid network
	• Signal spacing
	• Number of lanes
	• Pedestrian presence
	• Traffic control system
	  ○ Fixed-time
	  ○ Traffic responsive

Network Traffic Patterns	• Traffic volumes • Turning movements • Variability in traffic volumes • Level of congestion ○ Impact of congestion of bus travel times

Frequency/Characteristics of Transit Service	• Bus volume
	• Bus operations
	  ○ Express Service
	  ○ Local Service
	• Transit routes (e.g., conflicting bus movements at traffic signals)
	• Bus stop location/design
	• Amount and variability of dwell times
	• Communication and monitoring equipment of transit vehicles

Intersection Spacing

Intersection spacing may impact the detection system used and how priority is provided if the bus is detected at more than one signal. Intersection spacing only becomes a critical factor, impacting the performance of signal priority, when traffic volumes are high. At high volumes, as the intersection spacing increases, priority becomes less effective as the bus may be impeded by queues from a downstream intersection.

Bus Dwell Times

Transit priority is only impacted by bus dwell times at near-side bus locations. At near-side bus stops, the amount of time provided for priority may be increased to include the dwell time of the bus at the bus stop. At locations where the number of passengers loading and unloading is large and dwell times are long, holding the green or providing a green extension may result in priority being provided when the transit vehicle is unloading and loading passengers. At far-side locations, the bus dwell time has little to no effect on the effectiveness of priority. Far-side bus stop locations would seem to be the most effective location for bus stops when using green hold or green extension priority control. At far-side bus stops, the amount of time provided for priority is a function of the travel time through the intersection only.

Pedestrian Volumes

When priority is initiated, the controller must initiate or complete certain phases to provide minimum greens for vehicular and pedestrian clearances. The volume of pedestrians does not directly impact the effectiveness of priority, but when large number of pedestrians exist at the intersection, the need to maintain minimum green times to handle these pedestrians will limit the amount of priority that is available.

Pre-Implementation Check-list

To assess the suitability of signal priority in an area, Chada[1] provides a pre-implementation checklist that evaluates critical factors that may impede the benefits of signal priority. The checklist is shown in Table 2 and includes questions about the type of bus service, location of bus stops, presence of oversaturated cross-street conditions, and the number of buses operating on the roadway where signal priority is to be implemented. Each answer receives either zero or one point. The total points received can then be used to assess the suitability of an area for signal priority or the need for changes to ensure signal priority results in beneficial conditions. Table 3 provides the recommendation for implementing signal priority based on the results of the pre-implementation checklist.

Table 2. Pre-Implementation Checklist

Pre-Implementation Checklist	If Answer is "Yes"	If Answer is "No"
Express bus service	1 point	0 points
Express bus service during off peak?	1 point	0 points
Farside bus stops?	1 point	0 points
Highly saturated cross streets over 1.0 v/s ratio?	0 points	1 points
Heavy volume intersections in network?	0 points	1 points
Many instances of two transit vehicles approaching one intersection?	0 points	1 points
Do you have AVL technology installed?	1 point	0 points

Source: Chada[1]

Table 3. Recommendations of Pre-Implementation Checklist

Total Checklist Points	Recommendation
1-2	Changes need for priority
3	Priority somewhat recommended
4	Pursue priority
5-6	Priority strongly recommended

SCRITS Signal Priority Benefit Assessment

The Federal Highway Administration (FHWA) developed a sketch-level analysis tool to identify possible benefits of various Intelligent Transportation Systems (ITS) applications including signal priority. The analysis tool, referred to as SCRITS (SCReening for ITS), analyzes the time savings for buses and the additional delays to the side street as a result of the priority system. Table 4 shows an example of SCRITS for assessing the benefits of signal priority. Using inputs provided by the user, the annual value of passenger time savings and the annual value of vehicle passenger time savings (or costs) is used to determine the benefit cost ratio for implementing signal priority within a corridor. The assessment tool was not used in this study, but is provided to identify additional factors that should be considered when assessing the suitability of transit priority for an area.

Potential Locations

The research team attempted to identify potential locations for evaluating signal priority by first identify high volume arterial roadways within the State and then identifying transit corridors. Routes designated as both high volume and within transit corridors would then be investigated to determine the characteristics of the roadway and the appropriateness for implementing signal priority.

To identify high volume routes, the New Jersey Department of Transportation Data Reference System was used to determine roadways with the highest average annual directional traffic (AADT). The research focused on roadways found within the State's designated Urban Centers. The urban centers, as stated in Table 5, provided a geographical mix of locations within the State. These locations were also believed to provide locations with high numbers of bus passengers. Bus routes on these roadways were then identified using the New Jersey Transit website. These routes were identified by first selecting all routes traveling within the particular urban center. Line diagrams, which provide portions of the bus routes, were then viewed to identify the roadways used by the bus routes. Bus routes coinciding with high volume roadways were then identified. Finally, information on the number of lanes, number of signalized

Table 4. Signal Priority Benefit Assessment (Source: FHWA)

ANALYSIS OF BUS PRIORITY SYSTEMS		
	User Input	Calculated Value
Date of analysis	9/24/1998	
Scenario	Alternative 3	
Analyst	Smith	
Description of improvement	Bus priority on 10 miles of arterial X	
BUS OPERATIONS, WEEKDAY ONLY		
Miles on which priority treatment is implemented	10	
Number of buses per weekday on priority routes	64	
Current average bus speed on arterials (mph)	15	
Percentage of bus travel time attributable to signal delay	25%	
Estimated % reduction in signal delay from pre-emption	40%	
Average minutes per mile for buses without priority		4.00
Average minutes per mile for buses with priority		3.60
Average bus speed with priority (mph)		16.67
Percentage increase in bus speed		11.1%
Number of route-hours saved per day		4.3
Number of route-hours saved per year, weekdays only		1067
Number of daily passengers on affected routes	1,800	
Average passenger trip length (miles)	5	
Person hours without priority, weekday only		600
Person hours with priority, weekday only		540
Savings in person hours per weekday		60
Savings in person hours per year, weekdays only		21,900
Elasticity of demand with respect to bus speed	0.3	
Estimated increase in average weekday passengers on route		60
Daily vehicle trips on corridor served by bus route(s)	25,000	
Percent reduction in vehicle trips in bus corridor		0.24%
Annual value of time savings for bus passengers		$240,900
TRAFFIC OPERATIONS		
Weekday daily volume of cross street traffic for entire route	50,000	
Percentage of traffic that incurs pre-emption delay	10%	
Average delay time per pre-empted vehicle (sec.)	12	
Additional vehicle hours delay per day to cross street traffic		17
Additional person hours delay per day		22
Additional person hours delay per year		7,908
Annual value of vehicle passenger time savings, weekdays only		-$113,089
COSTS AND BENEFITS		
Total of bus passenger and vehicle passenger time savings		**$127,811**
Installation cost	$500,000	
Service life (years)	10	
Annual operating/maintenance cost	$50,000	
Operating cost per bus route-hour	$40	
Annual bus operating cost savings		$42,667
Annualization factor		0.142
Total annualized cost		$78,333
Annualized benefits (weekday only) minus annualized cost		$49,478
Benefit/cost ratio weekday only		1.6

Table 5. New Jersey Urban Centers

City	County
1. Atlantic City	Atlantic County
2. Camden	Camden County
3. Elizabeth	Union County
4. Jersey City	Hudson County
5. New Brunswick	Middlesex County
6. Newark	Essex County
7. Paterson	Passaic County
8. Trenton	Mercer County

intersections and other geometric information was obtained from NJDOT's Straightline diagram for each of the roadways identified. The search identified 28 locations, which are shown in Table 6.

Site Visits

Based on the review of geometric conditions and bus activity on the routes, sites with the most promise were selected for visiting and gathering further information. Sites in Camden and Mercer Counties were not visited as these sites did not indicate a large number of buses using the roadways. The following provides a discussion of some of the visits to these locations.

Ferry Street, Newark

Ferry Street is a two-lane municipal roadway that extends for approximately 2 miles in the City of Newark. Ferry Street is a two lane-two-way roadway extending from the Raymond Plaza/Market Street intersection to the west to Raymond Boulevard to the east. The street is located in the historic Ironbound District of Newark with several restaurants and businesses located on the roadway. The volumes on the roadway are high during the peak hour, with sufficient bus passengers and bus volumes to warrant consideration of signal priority on this street. Three bus routes stop on Ferry Street. The location of this street adjacent to Penn Station, however, results in more bus lines using the roadway. The signal density on the route is approximately 8 signals per mile, with the average distance between signals about 700 feet, although three locations have the minimum distance between signals of 264 feet.

Broad Street, Newark

Broad Street is a major roadway that extends for approximately two miles within the City of Newark. The roadway is designated as an urban principal arterial with between 4 to 6 travel lanes provided and about 4 signals per mile. Volumes

Table 6. Potential Locations for Implementing Signal Priority

County Name	*City*	*Route Number*	*Street Name*	*2-Way Volume*	*No of Lanes*	*Width (ft)*	*No. of Signals*	*Speed Limit*	*Bus No. by City*
Essex	Newark		Ferry Street	NA	2	40	8	25	1,25,34
	Newark		Broad Street	30,585	6	90	37	NP	41,42,43, 44,59,61, 62,65,66, 67,70,71, 72,73,74, 75,76,78, 79,90,
	Montclair	506	Bloomfield Avenue	23,740	4	56-60	33	25-35	11,28,34, 92,93,94, 96,99,
	Belleville	7	Washington Avenue	NA	4	60	10	30	13
Camden	Cherry Hill	38	Kaighn Avenue	50,940	4	50	8	50	450
	Lindenwold	673	Laurel Road	36,260	2	36	8	25	454,459
	Haddon	130	Crescent Blvd	36,200	4-5-6	36-48-36	6	40-45	
	Gloucestor	534	Clementon Road	26,650	2-4-2	24-40-72	6	40-45	403
	Cherry Hill	673	Springdale Road	22,794	2-3-4	34-40	7	40-45	406
Mercer	Trenton		Liberty Street	13,144	2	30	7	25	
	Trenton	653	Calhoun Street	23,800	2	43-34	8	NP	606
	Trenton	206	Brunswick Avenue	20,940	2	40	10	25	
	Trenton	650	Lalor Street	20,790	2	30	2	NP	607
	Trenton	33	Greenwood Avenue	17,150	3-2	36-40	12	25-30	606
Hudson	Jersey City	501	JFK Blvd	22,047	4	60	95	25	2,80,84,8 8
	Jersey City		Palisades Avenue	21,380	1-2	30-50	20	25	84,87,89
	Jersey City	602	Danforth Avenue	13,540	2	40	8	25	80
	Jersey City	617	Summit Avenue	12,570	2	30-45	22	25	80,83,84, 85,87

Table 6. Potential Locations for Implementing Signal Priority

County Name	*City*	*Route Number*	*Street Name*	*2-Way Volume*	*No of Lanes*	*Width (ft)*	*No. of Signals*	*Speed Limit*	*Bus No. by City*
Atlantic	Atlantic	87	Huron Avenue	28,640	4-5-6	50	3	45	501,505
	Atlantic		Atlantic Avenue	27,443	4	66	27	30	501,502,504,505,507,508,509,554
	Atlantic		MLK Blvd	NA	4-2	40-30	9	25-35	505,554
Passaic	Paterson	601	Main Street	18,688	2	40	5	NP	702,703,704,707,744,746,748,770
	Paterson		Broadway Avenue	NA	2-4	42-52-24	10	NP	72,74,704,722,744,748,770
Middlesex	New Brunswick	680	Howes Lane	21,062	2	40	3	NP	
	New Brunswick	-	New Street	11,352	2	40	4	25	
	New Brunswick	27	Somerset Street	22,740	4	40-30	31	40-25-30	
Mercer	Princeton	27	Nassau Street	11,521	2	24-52	8	25-45	
Monmouth	Avon-by-the-Sea	71	Nassau Street	11,521	2	24-52	8	25-45	

on this roadway are one of the highest for local roadways providing both access to businesses located on the roadway and providing mobility through Newark and to adjacent communities. The roadway also is a heavy transit corridor with over 20 bus routes using Broad Street. Broad Street intersects with several major roadways including Interstate 280, Route 21 (McCarter Highway), Route 510 (Market Street), and Route 508 (Central Avenue).

Route 506 (Bloomfield Avenue)

Bloomfield Avenue is an urban principal arterial roadway that extends for approximately ten miles in Essex County. The roadway has between 4 and 5 travel lanes with about 5 signals per mile. Roadway volumes vary throughout the length of the roadway but can be high during peak times and at locations of the roadway where businesses are present. The roadway has eight bus lines traveling on this roadway.

Route 7 (Washington Avenue), Belleville

Route 7, Washington Avenue, is one of the few State routes with a bus route in Essex County. The roadway extends for about ten miles from Jersey City to Nutley Township. In Jersey City, the roadway does not have traffic signals and at this location, is not considered for signal priority implementation. The roadway has four travel lanes with about 3 signals per mile between North Bergen and Nutley. Volumes on the roadway are not the highest in the County, however, during peak periods, volumes are high at some locations on the roadway. There is one bus line using the roadway, however, this bus route, has several branches with high frequency during the peak periods.

Route 501 (JFK Boulevard)

John F. Kennedy Boulevard is an urban principal arterial extending for about 15 miles through the cities of Bayonne, Jersey City, and North Bergen. The roadway has one of the highest volumes in Hudson County providing access to businesses and residences located adjacent to the roadway and providing mobility through this region.

The roadway has between four and six travel lanes with parking generally provided on both sides of the roadway. Traffic signals have been placed at almost every intersection on the Boulevard with an average signal spacing of about 400 feet. JFK Boulevard is a heavy transit corridor for buses providing connections to rail at Journal Square, which is located on the Boulevard. The heavy vehicular volumes and large number of buses using the roadway makes this location difficult for installing a bus nub.

Route 601 (Main Street), Paterson

Route 601 (Main Street) and Broadway Avenue in Paterson were also identified as roadways with potential for installing bus nubs. These roadways were identified as having high bus volumes with several bus routes including a significant number of paratransit vehicles with routes between New York and New Jersey. In general, both roadways have two travel lanes with parking on both sides of the roadway. The large number of businesses result in significant pedestrians and bus patrons within the area. These locations, however, were not considered for considering signal priority due to high level of congestion in the area. The high number of double-parked vehicles and unscheduled stops by some of the paratransit vehicles, also created a complex area not amenable to signal priority.

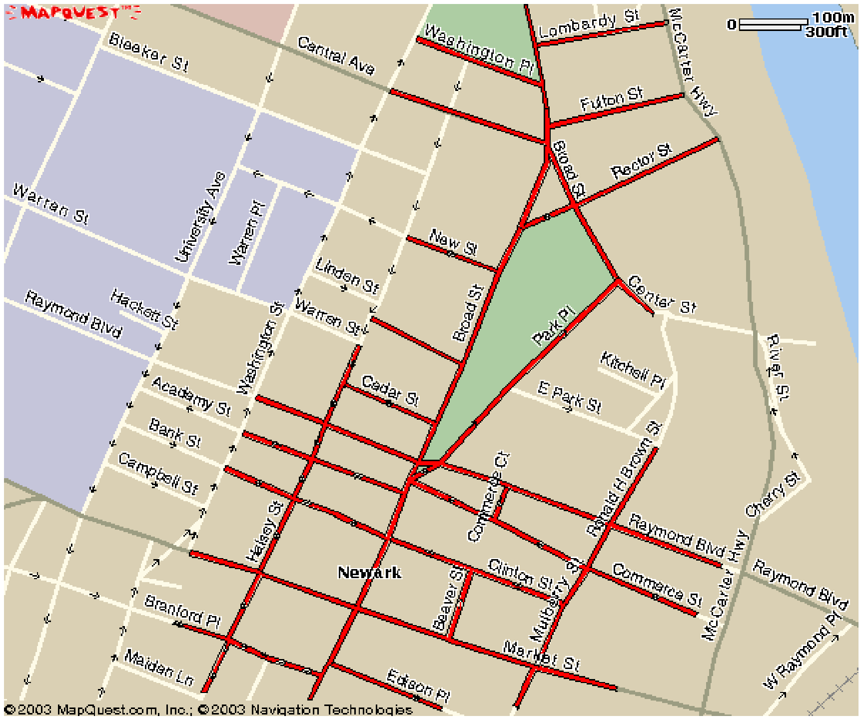


Figure 1. Broad Street, Study Area

Final Selected Locations

After an initial review, the location selected for further study for bus signal priority is Broad Street in Newark. This location, as shown in Figure 1, was selected because of the high number of bus routes and other vehicles on the roadway. The study area includes 15 signalized intersections and 2 unsignalized intersections, with 4 signals on Raymond Boulevard and 4 signals on Market Street.

Figures 2 and 3 show the existing volumes for Broad Street, as obtained from the City of Newark Engineering Department. These volumes were used in modeling conditions on the roadway.

Figure 2. AM Peak Hour Volumes

Broad Street – Volume Diagram (AM Peak)

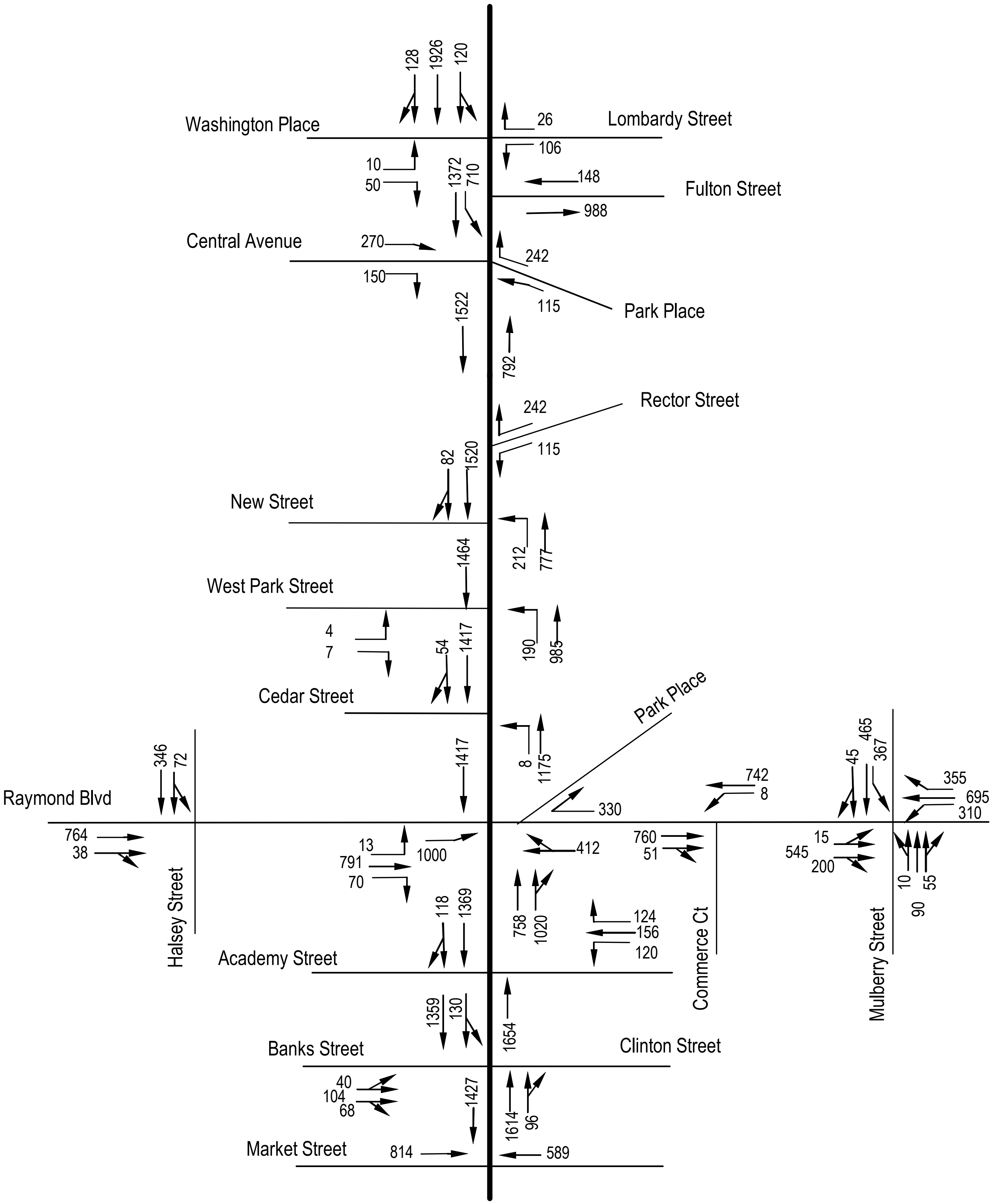
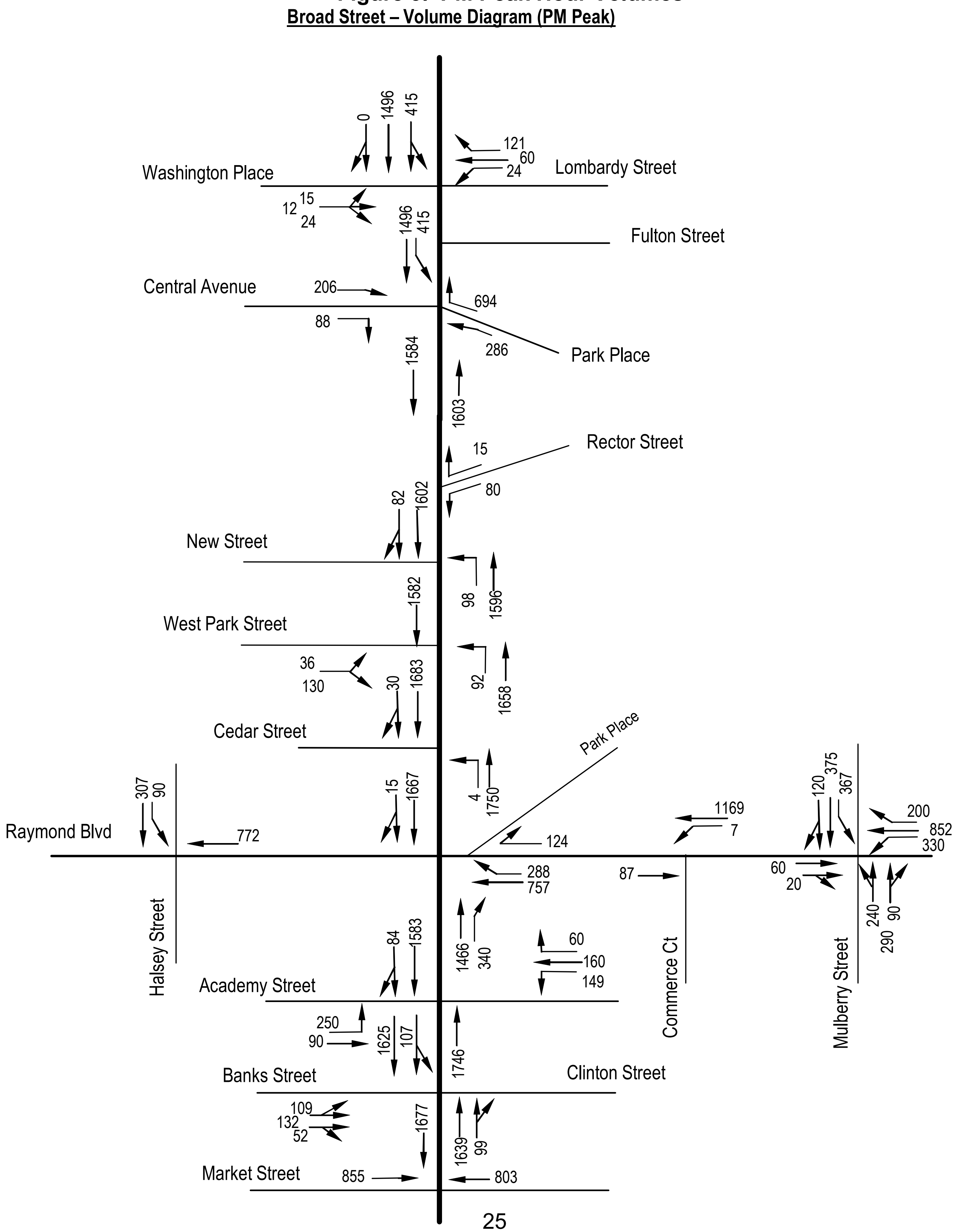


Figure 3. PM Peak Hour Volumes



SIMULATION STUDY

Overview

Simulation models of traffic flow have emerged as valuable tools for testing alternative strategies to enhance the flow of vehicles on highway networks. This Chapter describes the work effort and the results obtained associated with the application of a micro simulation model to analyze the existing arterial system that services a high volume of traffic and of transit vehicles.

KLD extended its WATSim (Wide Area Traffic Simulation) model[2] to incorporate transit signal priority control in a manner that replicates the current capability of existing systems. The model (a) represents the movements of individual vehicles over a highway network controlled by traffic signals and (b) incorporates such restrictions as bus-only lanes, turn restrictions, and other common treatments designed to expedite the movement of transit flow.

This in-depth study was conducted for a specific arterial system in downtown Newark, New Jersey. This is referred to as the “Broad Street Arterial”; it services approximately 22 transit routes during the Peak Hours.

WATSim© Modeling of Transit Preferential Signals

WATSim© offers two algorithms to determine the response of the traffic signal controller to a transit vehicle approaching an intersection operating with transit preferential signals. These algorithms are equally applicable to both bus and LRT transit and are known as “simple” and “complex”. They share certain characteristics. Both offer the ability to:

Extend Main Street green duration to service an approaching transit vehicle.

Advance the start of Main Street green (truncate Cross Street green) to minimize the time that a transit vehicle must wait to receive a green signal indication.

Restore signal coordination in the next signal cycle after any phase was extended or truncated.

This last feature preserves existing signal coordination and ensures that there is minimal disruption to general traffic flow as a result of transit signal priority. All controller decisions to either extend, advance, or do nothing, in response to an

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[2] Refer to Appendix II for a general description of the WATSim model.

approaching transit vehicle are subject to user specified constraints which are set for each intersection individually. Users also specify a “detection zone” along each approach over which the controller recognizes the presence of an approaching transit vehicle requesting signal preference.

Once a transit vehicle enters a “detection zone”, the logic identifies the current signal state, projects the vehicle’s travel time to the stop-bar (including any dwell time if a station is located on the approach), and determines a control decision: extend or advance the arterial green phase, or do nothing. The logic repeats this decision process each second until the vehicle clears the stop-bar.

The “simple” algorithm assumes that there is no detection equipment on the cross streets to measure current demand. This algorithm can be applied to intersections where cross street demand is low or is fairly uniform, and offers lower installation and upkeep costs since no cross street detectors are required. This algorithm allows cross street green phase duration to be shortened to a user-specified minimum duration when buses on Main Street can benefit, regardless of the current cross street traffic demand.

The “complex” algorithm requires detection equipment on the cross streets and uses these detectors to estimate current queue lengths and traffic demands. This information is used to determine the green time required to service cross street traffic demand. Thus, more sophisticated control decisions are computed dynamically to assure that adequate green time is always available to service the current cross street traffic.

Simulation Objectives

The objectives of this simulation were:

1. Develop a set of operational test plans delineating procedures for implementing and assessing transit signal priority systems.

2. Conduct a simulation analysis of a specific congested arterial system servicing a high volume of transit vehicles to quantify the operational benefits and adverse impacts of implementing bus priority signal systems.

3. Develop a methodology that utilizes these simulation results to identify bus routes that are candidates for priority control on a cost effective basis. This methodology will be organized so that NJDOT may investigate sites throughout the state to identify those where bus priority could provide the greatest benefits.

4. Document these findings in a format that would be most useful for State Engineers.

5. Develop conference and journal papers describing the research performed and the results obtained.

6. Present conclusions and recommendations based upon the results of this study.

Simulation Methodology

This section addresses the major activities, the general approach, the verification of model plausibility, and the experimental design.

Major Activities

The major activities performed were:

- Requested and received information identifying all bus routes that are serviced on the Broad Street arterial, as well as their respective schedules of operation during the AM and PM Peak Periods.

- Received supporting information in the form of design drawings and schedules of signal timing policies in effect during these peak periods.

- Obtained information detailing the traffic volumes and movements along this arterial system including turn movements at all intersections; obtained additional information on volume levels from NJIT.

- Obtained and verified information detailing the location of all bus stations and an estimate of bus dwell times.

- Performed a field survey of this arterial facility and obtained observational data describing the traffic signal timing and the dwell times experienced by buses at stations while servicing passengers. This field survey identified important differences between some of the data provided and information obtained directly through field observation, namely:

    1. The signal timing plan was made to conform to the field observations.

    2. In heavy flow situations, the fact that autos use the reserved bus lane as a “safety valve”, while still deferring to buses, was represented in the simulation.

- With the completion of the field survey, the data were organized and used as an input stream to the WATSim model, using KLD's UNITES interactive software system.

- An experimental design was developed to evaluate the benefits that would accrue from the application of bus priority control applied to this arterial section. Among the factors considered are:

  1. The effect of bus priority control on the operational characteristics of flow along this arterial section on the basis of the current signal timing and the current traffic volumes and turn patterns.

  2. The impact of bus priority control on traffic operations assuming that the traffic demand will increase by 10% and 20%--these were considered as "future" scenarios.

  3. Consideration of the impact of optimizing the traffic signal timing plan on traffic operations along this arterial system.

- This experimental design was applied for both AM and PM Peak Period traffic conditions.

- The data presented by the simulation model were segregated so that the performance of transit vehicles could be distinguished from that of the general traffic. In addition, the operational performance measures for the arterial traffic were segregated from those of the cross street traffic so that these two components of traffic could be analyzed separately.

- Furthermore, the data were organized to provide a platform for developing criteria that can be used to determine where the bus priority concept could be applied most effectively in the State of New Jersey.

This effort was designed to satisfy the project objectives stated in Section 4.0.

General Approach

To simulate traffic operations on the Broad Street network, traffic and geometric data were utilized to create WATSim inputs. After the data were entered, the WATSim model was executed to view the resulting computer animation, of traffic movements and to finalize the measures of effectiveness (MOE's) to be used in model calibration. The animation and MOE's were analyzed to determine whether the generated model properly represented traffic operations on Broad Street.

Field observations of signal timing, turn movements, and lane usage were made, and the data updated. The volume levels provided to us were used, because our own observations were not necessarily at the same time, and recorded lower volumes of general traffic.

As part of the lane usage, it was observed that compliance during the peak periods was generally very good, with the important exception that when the unrestricted lanes were crowded, passenger cars used the reserved lane as a “safety valve” (Refer to Figure 4 and Figure 5). They still tended to leave this lane as buses approached, and to move around stopped buses, but this “unauthorized” usage of bus lanes did benefit vehicle movements. The simulation model operated essentially the same way.

Verification of Model Behavior

After the simulation model was executed, the WATSim outputs were checked for consistency with the inputs. MOE’s such as bus dwell times, trips and headway distributions were compared to those of the field data. The animation was again compared to the actual traffic operation to ensure that the observed traffic behavior (e.g., similar queue formations) was replicated by the simulation results. Following the verification of the model’s outputs and animation a number of simulation scenarios were designed to reveal the effects of a bus priority system on the Broad Street network.

Figure 4. Shared usage of the Reserved Lane along Broad Street

Figure 5. Shared usage of the Reserved Lane along Broad Street

Table 7. Experimental Design Scenarios

Scenario	Demand	Control	Transit priority operation	
1	AM peak	Existing	No	
2	AM peak	Existing		Yes
3	PM peak	Existing	No	
4	PM peak	Existing		Yes
5	Future AM peak	Existing	No	
6	Future AM peak	Existing		Yes
7	Future PM peak	Existing	No	
8	Future PM peak	Existing		Yes
9	AM peak	KLD Signal Timing Policy	No	
10	AM peak	KLD Signal Timing Policy		Yes
11	PM peak	KLD Signal Timing Policy	No	
12	PM peak	KLD Signal Timing Policy		Yes

Experimental Design

The simulation scenarios studied are presented in Table 7. The effects of implementing bus signal priority on the operation of transit and non-transit vehicles along Broad Street were examined for AM and PM peak hours with existing and future (+10% and +20% traffic growth) traffic volumes. In addition to these analyses, the separate effects of improving the signal timing plan on the operation of transit and non-transit vehicles along the Broad Street were also analyzed. Note that one hour of simulation was performed for each of the AM and PM peak hours.

Analysis of the Simulation Results: Scenarios 1-8

Detailed results are contained in an extensive set of tables in Appendix III. This section presents a summary of these results; the existing conditions without transit priority (Scenarios 1 and 3) are identified as the Base Conditions for both the AM and PM peak periods.

Figure 6 shows the results for Broad Street, for both directions, in the AM and PM peaks. The future traffic is 10% above the existing volumes. Another set was run with 20% above the existing volumes, but volumes that high tended to overload Broad Street SB in the PM Peak, Market Street in the AM Peak, and Raymond Blvd (WB in the AM, EB in the PM).

This figure shows:

a. A beneficial impact on both transit and other arterial traffic when transit priority is introduced (in the NB, 10-20% for transit and 5-10% for autos; less in the SB). This is the second set of bars in each part of Figure 6;

b. An expected increase in both bus and auto travel times (relative to the original base) when traffic grows by 10%, without any transit priority. This is the third set of bars in each part of Figure 6;

A strong recovery of almost all of the prior transit improvement for this “future” condition, when transit signal priority is applied. This is accompanied by a significant alleviation of the adverse impact on auto traffic. This is the fourth set of bars in each part of Figure 6.

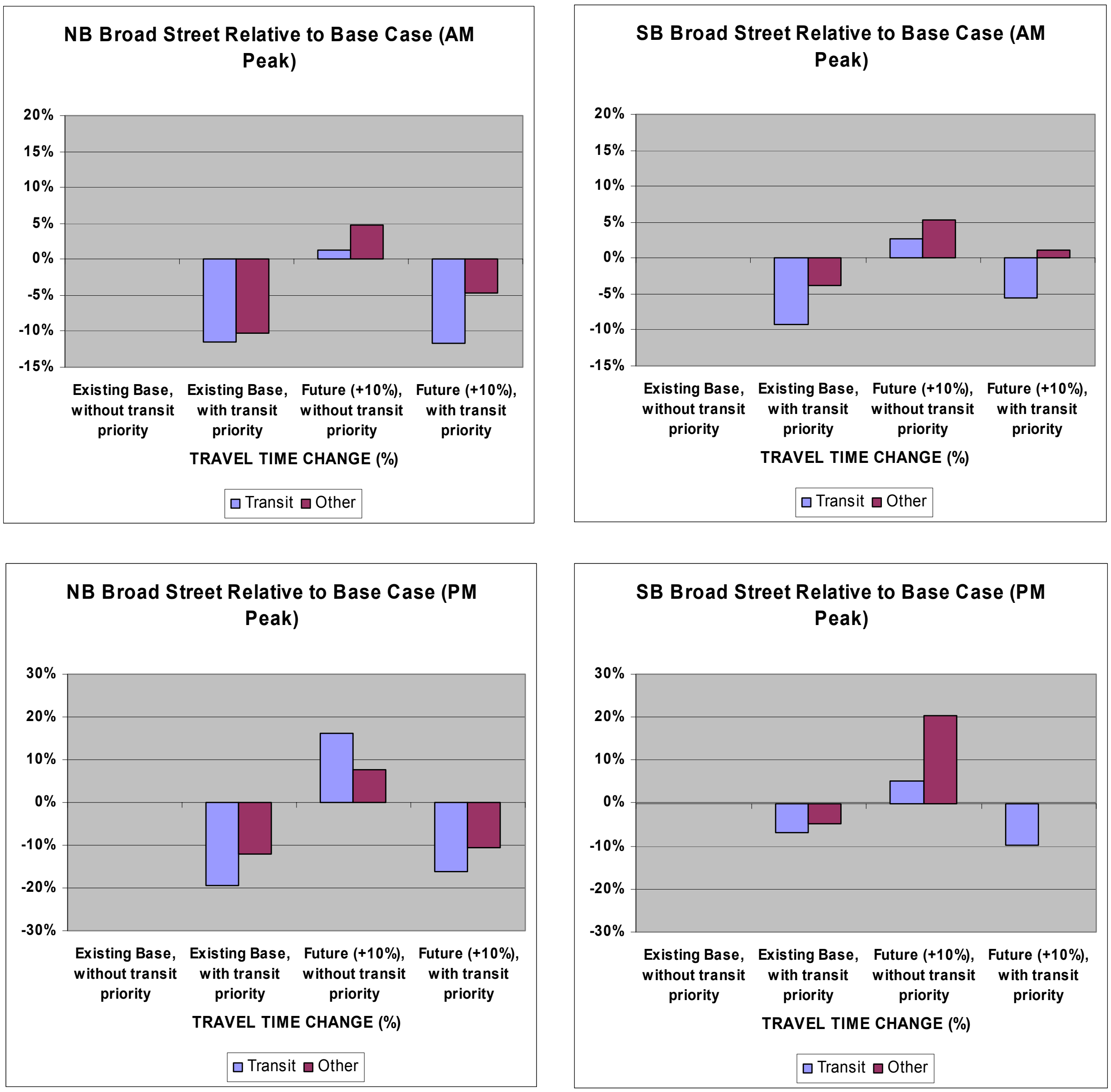

Figure 6. Impact of Broad Street Transit Priority on Broad Street Transit and Auto

At the same time, there are impacts on the cross streets. Figure 7 shows the effects on Raymond Blvd, and Figure 8 shows the effects on Market Street. Observe that:

a. On Raymond Blvd, when Broad Street transit priority is introduced, there are adverse impacts on both transit and autos in the EB direction during the AM, and on auto in the WB direction during the PM. In other cases, there are actually improvements to bus and/or auto travel times on Raymond Blvd;

b. On Market Street, when Broad Street transit priority is introduced, there are similar adverse impacts on both transit and autos in the EB direction during the AM, and on auto in the WB direction during the PM. In other cases, there are rather small adverse impacts to bus and/or auto travel times on Market Street;

c. As is logical, the travel time increases in the scenarios in which the traffic grows by 10% and the Broad Street transit priority is not yet introduced. This is shown by the third set of bars in each part of Figures 7 and 8;

d. While the Broad Street transit priority benefits Broad Street traffic for the 10% volume growth, this benefit comes at the expense of both Raymond Blvd and Market Street traffic, both of which experience *very* substantial increases in travel time. This is shown by the fourth set of bars in each part of Figures 7.

e. It is realistic to say that the 10% growth in demand volume cannot be accommodated if transit signal priority is implemented on Broad Street at these two intersections during the Peak Periods.

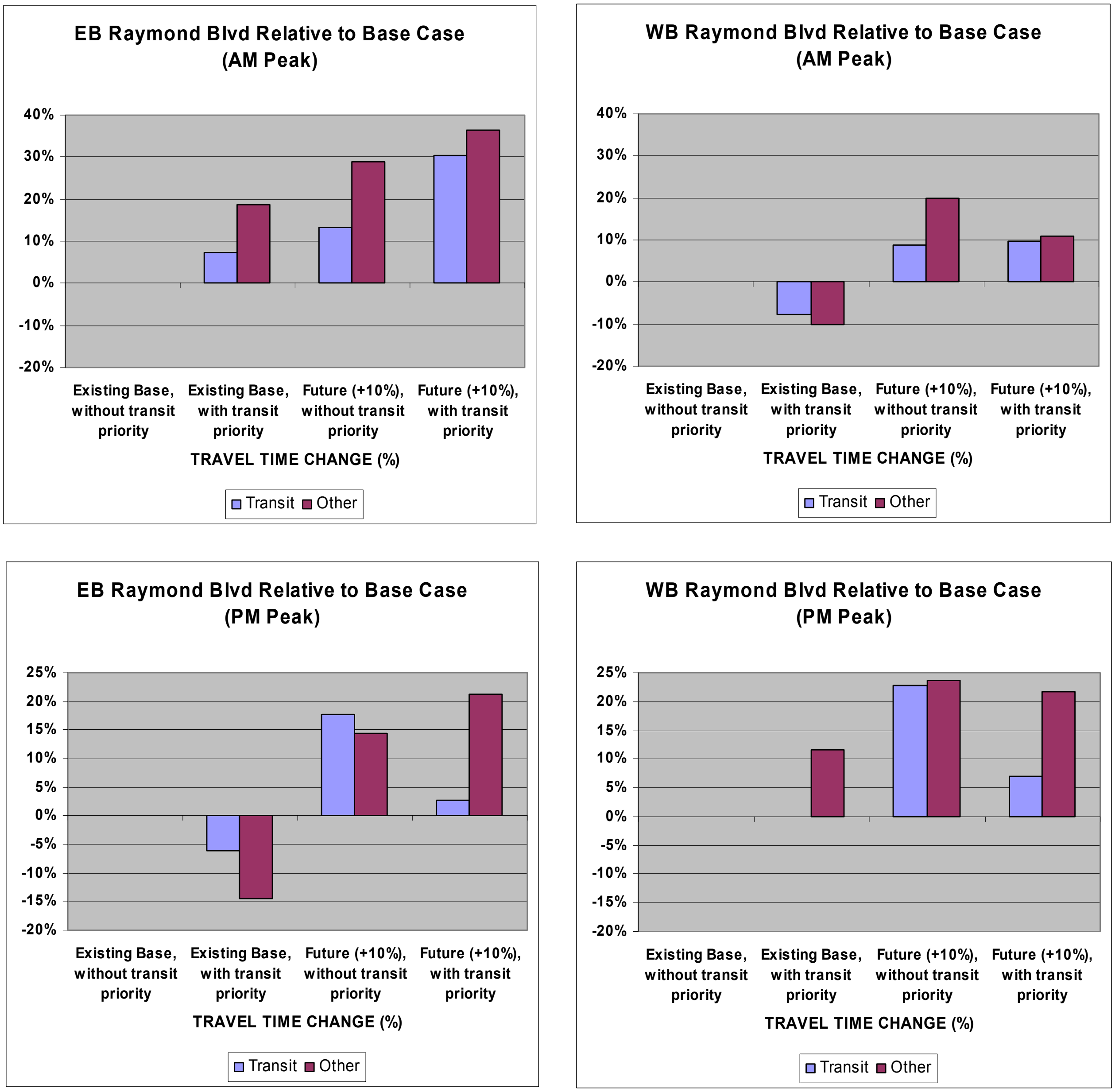

Figure 7. Impact of Broad Street Transit Priority on Raymond Blvd Traffic

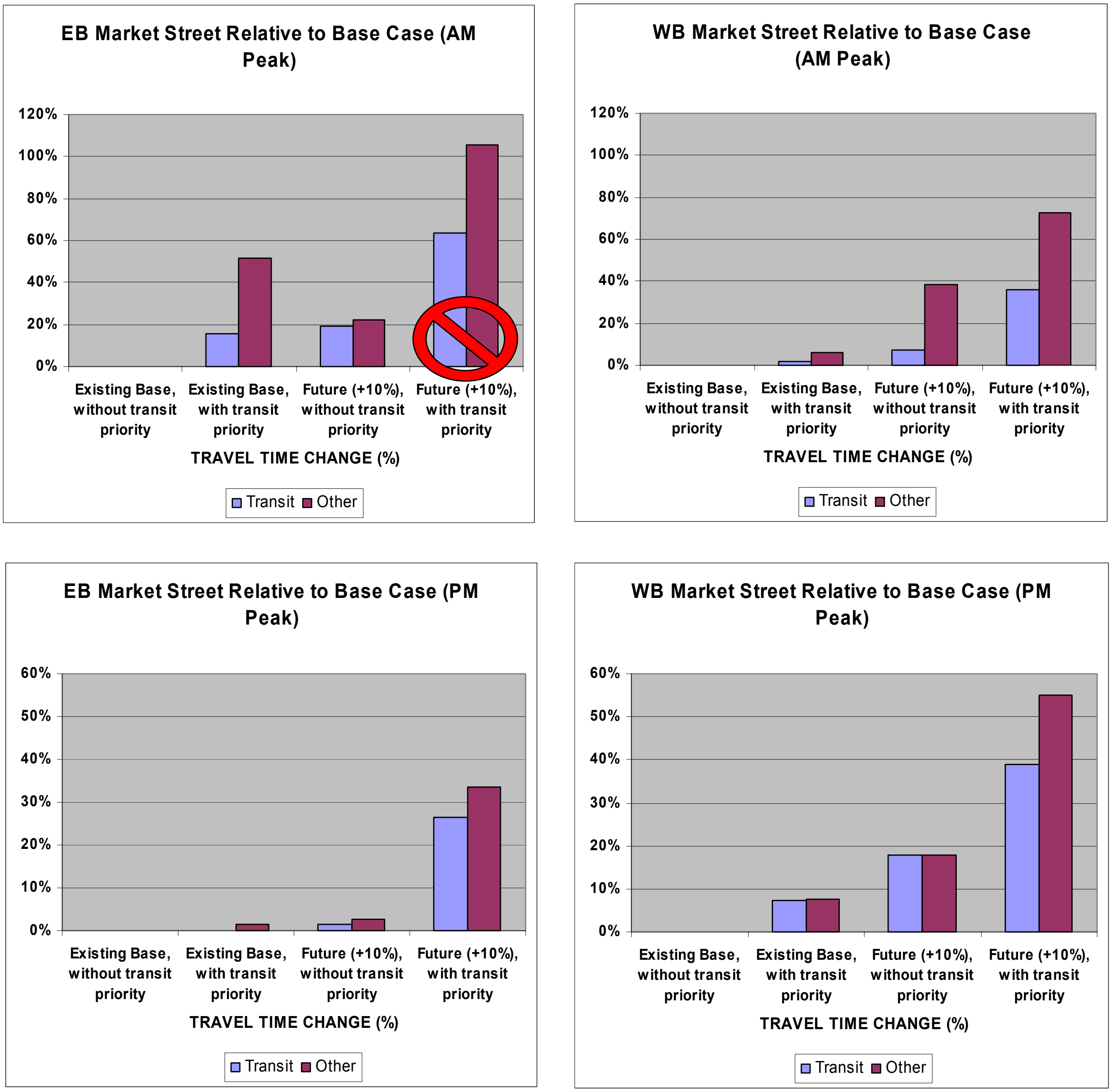

Figure 8. Impact of Broad Street Transit Priority on Market Street Traffic

Comparing Two Approaches: Signal Re-Timing Vis-à-vis Transit Priority

The preceding results occurred with the existing volumes and the existing signal timing (volumes were provided; signal timing was observed in the field; turning movements were observed at Raymond & Broad, but applied to volumes provided).

A logical question is whether a change in the existing signal timing could have beneficial effects on the transit and auto traffic, comparable to the advantages of the transit priority system. This was addressed by using a KLD signal optimization package; the results are displayed in Tables 8-10. The results on Broad Street are informative:

a. Improvements due to signalization changes equal or exceed those due to transit priority operating with the existing signal timing;

b. Nevertheless, there still is an incremental benefit due to the transit priority, albeit a smaller one (a further decrease of 4-6% in travel times, relative to the base case), operating with the improved signal timing.

It would appear that signalization updates would seem to be more cost-effective, once such an analysis was done. However, it is also true that transit priority has the practical effect of automatically updating the signal plan, should it become dated.

There are interesting results on the cross streets as a result of the network signal improvements and the Broad Street transit priority. These appear mixed, but are consistent with the traffic conditions:

- Raymond Blvd has substantial improvements during the PM peak in the EB direction due to signalization, with some small increases in travel time in the WB direction;

- During the AM peak, there are WB improvements to both transit and auto, and some EB adverse impacts on Raymond Blvd (on the buses only);

- The Broad Street transit priority tend to decrease these Raymond Blvd improvements somewhat, as would be expected, given the preference to Broad Street traffic. These improvements are not eroded by more than 50%;

Table 8. Effect of Broad Street Transit Priority from Existing and Improved Signal Plans, as Exhibited on Broad Street

BROAD STREET, AM PEAK — NB

From	To	BUS	AUTO
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	ADD BUS PRIORITY	-12%	-10%
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	IMPROVE SIGNALIZATION	-17%	-17%
IMPROVE SIGNALIZATION	ADD BUS PRIORITY	-21%	-20%

BROAD STREET, AM PEAK — SB

From	To	BUS	AUTO
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	ADD BUS PRIORITY	-9%	-4%
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	IMPROVE SIGNALIZATION	-9%	-18%
IMPROVE SIGNALIZATION	ADD BUS PRIORITY	-12%	-19%

BROAD STREET, PM PEAK — NB

From	To	BUS	AUTO
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	ADD BUS PRIORITY	-20%	-12%
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	IMPROVE SIGNALIZATION	-20%	-12%
IMPROVE SIGNALIZATION	ADD BUS PRIORITY	-24%	-19%
Modified (no priority at Broad & Market)		-23%	-16%

BROAD STREET, PM PEAK — SB

From	To	BUS	AUTO
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	ADD BUS PRIORITY	-7%	-5%
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	IMPROVE SIGNALIZATION	-19%	-24%
IMPROVE SIGNALIZATION	ADD BUS PRIORITY	-22%	-24%
Modified (no priority at Broad & Market)		-22%	-24%

Table 9. Effect of Broad Street Transit Priority from Existing and Improved Signal Plans, as Exhibited on Raymond Blvd

RAYMOND BLVD, AM PEAK — EB

	BUS	AUTO
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION → ADD BUS PRIORITY	7%	19%
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION → IMPROVE SIGNALIZATION	10%	1%
IMPROVE SIGNALIZATION → ADD BUS PRIORITY	15%	22%

RAYMOND BLVD, AM PEAK — WB

	BUS	AUTO
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION → ADD BUS PRIORITY	-8%	-10%
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION → IMPROVE SIGNALIZATION	-11%	-12%
IMPROVE SIGNALIZATION → ADD BUS PRIORITY	4%	5%

RAYMOND BLVD, PM PEAK — EB

	BUS	AUTO
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION → ADD BUS PRIORITY	-6%	-15%
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION → IMPROVE SIGNALIZATION	-21%	-43%
IMPROVE SIGNALIZATION → ADD BUS PRIORITY	-25%	-41%
Modified (no priority at Broad & Market)	-20%	-39%

RAYMOND BLVD, PM PEAK — WB

	BUS	AUTO
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION → ADD BUS PRIORITY	0%	12%
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION → IMPROVE SIGNALIZATION	10%	6%
IMPROVE SIGNALIZATION → ADD BUS PRIORITY	0%	4%
Modified (no priority at Broad & Market)	-3%	2%

Table 10. Effect of Broad Street Transit Priority from Existing and Improved Signal Plans, as Exhibited on Market Street

MARKET STREET, AM PEAK — EB

From	To	BUS	AUTO
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	ADD BUS PRIORITY	15%	51%
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	IMPROVE SIGNALIZATION	-8%	1%
IMPROVE SIGNALIZATION	ADD BUS PRIORITY	33%	68%

MARKET STREET, AM PEAK — WB

From	To	BUS	AUTO
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	ADD BUS PRIORITY	2%	6%
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	IMPROVE SIGNALIZATION	-3%	-5%
IMPROVE SIGNALIZATION	ADD BUS PRIORITY	3%	14%

MARKET STREET, PM PEAK — EB

From	To	BUS	AUTO
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	ADD BUS PRIORITY	0%	2%
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	IMPROVE SIGNALIZATION	-2%	0%
IMPROVE SIGNALIZATION	ADD BUS PRIORITY	50%	79%
Modified (no priority at Broad & Market)		7%	8%

MARKET STREET, PM PEAK — WB

From	To	BUS	AUTO
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	ADD BUS PRIORITY	7%	8%
BASE CONDITION VOLUMES, EXISTING SIGNALIZATION	IMPROVE SIGNALIZATION	21%	16%
IMPROVE SIGNALIZATION	ADD BUS PRIORITY	38%	63%
Modified (no priority at Broad & Market)		7%	8%

- On Market Street, there tend to be mild improvements to both buses and autos due to the improved signal plan, except on the WB direction in the PM peak (16-21% increases in travel time);

- <u>The addition of the Broad Street transit priority, on top of the signal plan changes, generally degrades Market Street dramatically</u>.

At first, these results (Table 10, PM Peak, Market Street, both directions) lead to the question: Can transit priority applied to an "optimized" signal plan impair Market Street mobility, whereas a not-optimal plan (i.e. the original one) did not have the same effect when transit priority was introduced?

The answer to this question lies in the relevant volumes of the different streets, in that Market Street was "pushed to the edge" by the new signal timing policy, but remained operating effectively --- as long as more green time was not taken away. But that is exactly what Broad Street transit priority does, to the extent that queues form much more readily on Market Street, as can be seen in the animation.

Of course, it is quite feasible to adjust the signal plan so that Broad Street has less advantage and Market Street has less adverse impact.

We chose to remove the transit priority from only the intersection at Broad & Market, with the results shown as "Modified (no priority at Broad & Market)" in Tables 8-10, at the bottom of each table. With little adverse effect elsewhere, Market Street no longer has an acute problem in the PM.

Close inspection of the results in Tables 8-10 reinforce the idea that, even with such policy decisions, <u>*transit priority can automatically (and continuously) deliver advantages at least comparable to regular signal plan updates*</u>. The agency in charge has to make a decision that includes a practical assessment of how often the signal plan can be updated over the coming years. If the answer is "infrequently" due to staff or other reasons, transit priority can provide a noticeable benefit.

The comparisons presented in Tables 8-10 are shown in Table 7 (Experimental Design) as Scenarios 1-4 and 9-12.

Reduction in Transit Vehicles

As a result of bus travel time reductions, one of the enticing questions that can be raised is whether fewer buses can provide the same frequency of service, in terms of total seats past a given bus stop during the peak hour, while providing lower travel time for passengers.

This question can be considered for two important cases:

- The present, when there is some potential;
- The future, when the number of additional buses needed might be mitigated.

The potential is illustrated in this section. It is understood that as an operational issue, additional factors have to be considered, including layover time at the route terminus.

Refer to Table 11, which illustrates the potential for reducing the number of buses.

Table 11. A Computational Sheet for Identifying Possible Operating Savings, if Fewer Buses are Needed due to Transit Priority Reducing Route Times

Length of Route, Round Trip	Frequency of Buses on that	Average Speed of Buses, without	Travel Time Change NB	Travel Time Change SB
6.0	3.0	12.0	-20.0%	-15.0%

Without Priority		With Priority			
10.0	Buses Needed to Serve the Route	9.1	savings of approx	1	bus(es)

% of Route		% Savings
25.0%	Full TT Savings	100.0%
50.0%	Fractional TT Sav	50.0%
25.0%	No TT Savings	0.0%
	Weighted	0.500

Sample Route Analysis

The key factors are shown in the upper part of the first box: the average bus speed and the length of route determine the route travel time; the route travel time and the scheduled bus frequency determine the number of buses needed in the base condition (lower left, upper box). In this example, the number of buses $= (6 \text{ mi}/12 \text{ mph}) \div 3 \text{ min.headways} = 10 \text{ buses}$

The travel time savings in the most congested area (e.g. the study area, in the case used) influences changes in the route travel time. Hence the number of buses needed with the improvement due to signal priority may be calculated as follows:

$$\underset{\text{RT Time}}{30\,\text{min}} \times \underset{\text{Reduction Factor}}{\left[1-0.5\left(\frac{0.2+0.15}{2}\right)\right]} = \underset{\text{Improved RT Time}}{27.4\,\text{min}}.$$

Then the number of buses is 27.4 / 3 = 9.1.

Thus, the number of buses servicing the route can be reduced to 9 by slight adjustments to the schedule.

The lower box in Table 11 needs to be explained. For this illustration, it was assumed that the indicated savings in travel time (-20 and -15 percent) are realized in the congested area under study which covers only 25% of the route; half of these savings are realized on 50% of the route; no savings on 25% of the route. The resulting 0.5 weighting factor is shown in the calculation.

One can generalize from the worksheet in Table 11, write the underlying equations and tabulate results for a range of bus route lengths, service frequency, average bus speed, and percent travel time saved. The important underlying principle is that for some combinations of these factors ---- notably longer routes, higher bus frequencies, lower bus speeds, and material savings in travel time due to bus priority --- there is an important potential for reducing the number of buses needed to service a route and to reduce operating costs.

Conclusions

Traffic simulation was used to effectively quantify travel time impacts and transit operational benefits due to transit priority. The primary conclusions are as follows:

1. Transit priority often reduced both transit and auto travel times on the route to which priority was applied, and had varied results --- but not at all always adverse --- on cross streets;

2. Transit priority can compensate for signal plans slipping out of date, which sometimes necessarily occurs due to limited resources or competing priorities;

3. Transit priority can forestall the need for other actions, in the face of traffic growth;

4. The benefits of transit priority are generally greater at higher traffic volumes;

5. The potential of transit priority to influence the number of buses needed to service a route does exist, and needs to be analyzed in the context of other operational factors (e.g. layover times at termini). Achieving a reduction in number of buses needed --- now or in the future --- can of course have significant operating cost benefits

Recommendations

The following action-oriented recommendations are made:

1. Review and, if needed, update the signal timing plans to benefit all traffic (transit and non-transit).

2. Identify transit routes that can benefit the most from transit signal priority; these are generally the longer routes, with high bus frequency, and low bus speeds due to congestion and high signal density. Transit priority can often result in material bus travel time savings (10-25%). Simulation studies – with properly detailed conditions – can quantify the savings for a particular route.

3. Field tests to verify the hypothesized savings is recommended, because it would add credibility to future simulation evaluations.

4. Travel time savings of transit priority can result in considerable economic benefit due to

   - person-hours of travel reduced;

   - future traffic growth better accommodated;

   - potential savings in number of buses needed (under certain conditions), at present or especially in growth scenarios;

   - de facto updating of the signal plan;

It is strongly recommended that a case study and/or checklist-based procedure be done in the near future.

OPERATIONAL TEST PLANS

Overview

To assist in the implementation of signal priority, operational test plans were developed to provide details on how signal priority can be provided within a test corridor in New Jersey. The plans provide details covering the general areas of: (1) Signal Priority Strategy; (2) Hardware and Software Requirements; (3) Operational Conditions; (4) Legal Requirements; (5) Evaluation Procedure; and (6) Budget. Details of the signal priority algorithm or strategy to be implemented will be provided. This information include details on the conditions that would trigger a call for signal priority. Data requirements, both in terms of quality and quantity, for implementing the strategy will be determined. The hardware and software needs for implementing signal priority at each of the locations will also be determined.

A description of additional technologies that could be included to enhance the signal priority implementation will also be provided. The operational characteristics of the roadway, both of transit and non-transit vehicles, will also be included. The operational characteristics will provide information on the potential impacts of signal priority on the roadway network. The evaluation procedure will include details on the data collection effort that should be associated with the operational test plan, measures of effectiveness to be determined, the types of statistical tests to be performed and the ideal number of intersections to be equipped. Finally, the budget will provide some projections about the costs for performing the operational tests.

Signal Priority Strategy

Based on the simulation analysis of Broad Street, the signal priority strategy proposed for Broad Street includes a *green extension* strategy, where the green time for the transit vehicle is extended when the transit vehicle is detected. In this approach, the green time is extended when the bus is detected. A second priority strategy considered in the simulation analysis and recommended for use on the arterial is the use of an early green. In this strategy, the movement where the transit vehicle is detected receives an expedited return to green.

To avoid the deterioration of traffic not favored by priority treatment, steps can be taken to compensate the non-transit movements. The approach recommended for use on Broad Street is to restore signal coordination in the next signal cycle after any phase was extended or truncated. Using this approach, any existing signal coordination would not be out of step and would be available in subsequent cycles.

Hardware and Software Requirements

The hardware and software requirements for implementing bus signal priority will depend on the type of bus priority system used. Generally, the components of a transit priority system include a transmitter that is located on the vehicle, a receiver at the intersection approach, a communication system that transfers information between the vehicle and either the local intersection or a traffic or transit management center, and the traffic signal control system that is obtains information about the priority request and makes appropriate changes to the signal timings. Three major bus priority systems have been used in North America. These include: Amtech radio frequency technology; 3M™ Opticom™ Priority Control System; and Vetag. The following provides a brief description of these technologies.

Amtech Radio Frequency

The Amtech Systems Division pioneered the development of dedicated short-range communications (DSRC) systems using radio frequency (RF) technology [16,17]. The system consists of tags, antennas, and readers. The tag or transponder is located on the upper right front corner of the bus. Readers, located on the street, broadcast RF energy to an area called the "read zone". The tag reflects a small part of this RF energy back to an antenna producing a unique identification code used to identify the vehicle. The tag can also transmit data packets that may include static data such as the agency name, vehicle ID, as well as dynamic data such as the driver number, route, run, trip, and class. The dynamic data is sent to the tag upon driver log-in via the on-board Tag Interface Unit (TIU). The tag remains passive until activated by the roadside antenna and Amtech tag reader unit.

The antenna is either pole or mast-armed mounted and is located between 500 and 1000 feet in advance of the intersection. An interface between the reader and the traffic controller is also used to process information received by the tag and to determine whether priority will be provided. This interface, referred to as the Transit Priority Request Generator. A base computer is used to communicate between various Transit Priority Request Generator systems in the field. The computer can be access the Request Generator via modem with the ability to upload operations and transponder logs, and to download programmable settings to the Request Generator subsystems.

3M™ Opticom™ Priority Control System

The 3M™ Opticom™ Priority Control System provides temporary advantage to individual buses, as needed, to help them catch up to schedules and maintain progression. It does this in three steps that occur within seconds:

- An emitter mounted on the bus is activated to send encoded infrared communication. The emitter's communication signal is encoded with a unique vehicle identifier and user authorization code. A variety of application-specific models are available. The 3M™ Opticom™ Priority Control System Model 492 Emitter is a compact, lightweight, weather resistant encoded signal device intended for use on priority vehicles. A variety of in-vehicle switches are available to operate the Opticom emitter. The emitter switch has fully enclosed push button switches (with dashboard mounting brackets) with an On/Off probe frequency selection.

- A detector located near the intersection receives the signal and converts it into electronic communication. The detector then sends the electronic signal to the phase selector in the signal controller cabinet. The 700 Series Opticom detectors transform the infrared signal detected from an approaching, vehicle-mounted Opticom emitter to an electrical signal. The electrical signal is transmitted along a cable to the Opticom phase selector or discriminator for processing. Detectors are mounted at or near the intersection to permit a direct, unobstructed line-of-sight to vehicle approaches. Detectors may be mounted on span wire, mast arms, or other appropriate structures.

- Phase selectors are plug-in, two or four channel, dual priority, encoded signal devices designed for use with 3M™ Opticom™ Priority Control System emitters and detectors. Versions for NEMA traffic controllers are also available. The phase selector, which is housed in the controller cabinet, presents a priority request to the traffic controller. Discriminators, which are used to check the authorization of the vehicle, can be installed directly into the input file of Type 170 traffic controllers equipped with priority phase selection software. The phase selector also logs management information and requests priority advantage for the controller to extend a green light. If two authorized vehicles approach the intersection at the same time, the priority control request is given to the vehicle assigned the higher priority.

When used by public safety personnel, the vehicle operator flips a single switch to activate the emitter. For transit applications, the driver controls the use of the emitter or it can be controlled by 3M Integrated Fleet Operations (INFO) System. The INFO system uses global positioning satellites and computers to track transit fleet vehicles and the Opticom system to help them stay on schedule. [18]

The system can operate over a range of 200 to 2500 feet. As transit operators generally require shorter ranges, the equipment can be programmed to accommodate the needs of public transit vehicles. The Opticom system use Wapiti Type 170 software to operate. Opticom can be used with AVL information such as: Service Date; Vehicle Number; Train No. (Block); Badge Number; Route; Day Type; Trip Number; Scheduled Time; Actual Arrive Time; Actual Leave Time; Dwell; Door Open (yes or no); Lift Used (yes or no); Maximum Speed; Distance Between Stops; and X & Y Coordinates.

VETAG

VETAG (VEhicle TAGging) system is a communication system that provides one-way communication from a wayside location to a vehicle[19]. The system, which is marketed by the Dutch transportation company Peek Traffic, was developed to allow automatic identification of vehicles. VETAG uses a transponder, which is placed under the vehicle, and transmits a unique identification signal to a detector. Detection is accomplished through induction loops which are placed in the road surface and are linked to a Base Wayside Station (BWS).

In addition to providing vehicle identification, VETAG also can be used to determine the position of a vehicle, the time the vehicle arrives at a location, provide information that can be displaced at bus stops and can be used to provide priority to transit vehicles.

VETAG appears to be primarily used for rail systems and may not be appropriate for bus signal priority. Little information could be found on the operation of this system in field conditions.

Operational Conditions

Chapter IV provides the results of the simulation of Broad Street under bus priority. The simulation demonstrates that providing priority to transit vehicles on Broad Street can result in bus travel time savings with significant increases in delay to non-transit vehicles.

Legal Requirements

The New Jersey Department of Transportation Electrical Department has designed specifications for optically controlled emergency vehicle detection system. These specifications are provided in N.J. Specification No. EB-EOVD. It has to be determined whether these specifications can also be used for providing transit detection.

Evaluation Procedure

An evaluation of a bus priority strategy requires evaluating several components including:

- Impact of bus travel time
- Impact of cross street delay

- Impact of bus delays at intersections
- Driver and public perceptions
- Equipment evaluation

The following provides a description of an evaluation procedure for each component of a bus signal priority evaluation.

Impact of Bus Travel Time

To determine the impact of bus priority on bus travel times, travel times of buses would need to be measured both during non-priority bus trips and when priority is used. Bus travel times would be measured both for the entire length of the route and between signalized intersections. Travel times would be measured for a low, medium and high volume conditions, as well as under different priority strategies. Several methods exist for collecting bus travel time data. Some of these methods include:

- License plate matching;
- Manual on-board observation using a stopwatch; or
- Shadowing the bus in another vehicle.

The choice of method depends on the length of the segment and number of data collectors available.

Impact of Cross Street Delay

To determine the impact of bus priority on cross-street delay, vehicular delay would need to be measured at either all cross-streets or critical cross-street locations during time periods when priority was provided and no priority is provided. Although the cross-street delays are of greater concern, delays for all approaches to the intersections, including the major arterial, should be collected. Delay is primarily measured using manual techniques. Using this approach the number of stopped, locked wheel, vehicles is counted every 15-seconds for a length of time. The total number of vehicles discharging from the intersection is also measured at the same time and used to determine the average delay per vehicle discharged from the intersection.

Impact of Bus Delays at Intersection

To determine the impact of bus priority on bus delays at intersection, bus delays would need to be measured both during non-priority bus trips and when priority is used. Bus delays at intersections can be measured at the same time that the bus travel times are determined. This would be accomplished by also gather the bus running time, time the bus is actually moving, while collecting the bus travel time. To determine the running time, all delays experienced by the bus would be measured separately. For bus delays due to a traffic signal, the time the bus stops at the traffic signal and the time the bus reaches some minimum threshold speed would be noted and the difference between the two times taken as the bus delay. Software exist for collecting travel time data from companies such as Jamar Technologies.

Bus delays at intersections can also be determined by reviewing the bus detection duration. This is accomplished using the vehicle detection equipment used by the bus priority system. The assumption of this approach is that the length of time the bus is detected is proportional to the amount of delay the bus experiences. This approach would only be appropriate at far-side bus stop locations.

Impact of Driver and Public Perceptions

To determine the impact of bus priority on driver and public perceptions, surveys and focus groups of these groups would have to be performed some time after priority has been implemented on the route. The types of information to be gathered by bus operators include difficulties in operating the system or unintentional consequences associated with implementing bus priority on the route. General questions about the perceived benefit of bus priority from bus patrons, and non-transit users would also be gathered.

Evaluation of Equipment

An evaluation of the equipment used would be performed to identify where the equipment may fail in its performance. The optimal location of detectors would be evaluated and the impact of geometry on emitter performance would be evaluated.

CONCLUSIONS AND RECOMMENDATIONS

Overview

This report summarized the results of the work performed under the project *Assess Impacts and Benefits of Traffic Signal Priority for Busses.* The research objectives were to assess implementation issues associated with the use of bus signal priority in New Jersey, develop operational test plans for implementing signal priority at promising locations, and assess the benefit and costs of signal priority. The research provides a comprehensive and critical review of transit signal priority systems. Potential locations for implementation of signal priority in New Jersey were identified. A simulation study performed on an arterial was used to assess the benefits and determine the operational impacts of signal priority.

Research Summary

Bus signal priority has the potential to save bus travel times and attract additional riders away from automobiles to transit. Priority also has the disadvantage of penalizing the cross-street traffic when high transit volumes exist at the corridor. Despite the potential benefits of bus signal priority, this technique has been more popular in Europe. The magnitude of the benefits associated with signal priority depends on the type of system that is implemented and the traffic conditions in the area. Differences in roadway and volume conditions can affect the results.

The overall benefit or effectiveness of transit priority is a function of several factors related to the geometric configuration, traffic conditions, and transit service where the transit priority scheme will be implemented. Bus volumes impact the number of priority calls that are placed on the arterial. Too few buses may make the investment in the priority system questionable and heavy bus volumes may increase delays to vehicles on the cross-streets or to movements not served by the transit vehicle. Far-side bus stop locations are the most effective location for bus stops when using green hold or green extension priority control. The volume of pedestrians does not directly impact the effectiveness of priority, but when large number of pedestrians exist at the intersection, the need to maintain minimum green times to handle these pedestrians will limit the amount of priority that is available.

To assess the suitability of signal priority, information about the type of bus service, location of bus stops, presence of oversaturated cross-street conditions, and the number of buses operating on the roadway where signal priority is to be implemented is needed. Potential locations for evaluating signal priority in New Jersey were identified by identifying roadways with high volumes and located within a transit corridor. Routes designated as both high volume and within transit corridors were then investigated to determine the characteristics of the roadway and the appropriateness for implementing signal priority.

To assess the benefits and costs associated with implementing signal priority, a simulation study was performed of Broad Street in Newark. Broad Street was selected based on the recognized transit corridor on the roadway, the roadway and bus passenger volumes that suggested that priority may be warranted, and the availability of data. The study area includes 15 signalized intersections and 2 unsignalized intersections on the primary arterial, and 8 signalized intersections on two of the major cross-streets. The simulation study incorporated transit signal priority control in a manner that replicated the current capability of existing systems. The objective of the simulation study was to delineate procedures for implementing and assessing the implementation of a transit signal priority system in New Jersey.

The effects of implementing bus signal priority on the operation of transit and non-transit vehicles along Broad Street were examined for AM and PM peak hours with existing and future (+10% and +20% traffic growth) traffic volumes. The study found a beneficial impact on both transit and other arterial traffic when transit priority was introduced. There was an expected increase in both bus and auto travel times (relative to the original base) when traffic grows by 10%, without any transit priority. At the same time, there were adverse impacts to the cross streets of Raymond Blvd. and Market Street. However, improvements due to signalization changes equal or exceed those due to transit priority operating with the existing signal timing. As a result of bus travel time reductions, the number of buses servicing the route was determined to be reduced to 9 by slight adjustments to the schedule. The important underlying principle is that for some combinations of these factors ---- notably longer routes, higher bus frequencies, lower bus speeds, and material savings in travel time due to bus priority --- there is an important potential for reducing the number of buses needed to service a route and to reduce operating costs.

Guidelines

Bus signal priority should be considered in locations in New Jersey that have the greatest potential to achieve the benefits associated with its installation. These benefits include:

1. Reduce transit travel times;
2. Improve transit schedule reliability; and
3. Make transit more reliable.

Based on the research performed, bus signal priority should be considered at locations with when the following factors are present:

- A significant portion of the bus delay is at signalized intersections;
- Bus stops are located at the far-side of the intersection;
- Bus volumes are between 10 and 20 buses during the peak hour;
- Express bus service is preferred over local service;
- All vehicles queued at signalized intersections discharge in one cycle;
- Level-of-Service for the cross-streets is D or better;
- Bunching of buses at bus stop does not occur;
- Pedestrian volumes are low to moderate;
- Where AVL technology exists or is planned.

Conclusions

The research demonstrates that bus signal priority can be effective in New Jersey with significant benefits associated with this treatment. The research also demonstrates that bus signal priority may not be appropriate at heavily congested locations or locations serviced by local buses with frequent stops. A successful implementation of signal priority warrant careful consideration of not only the transit impacts, but the vehicular impacts. Simulation has proved to be a necessary first step in determining the appropriateness of implementing a bus signal priority treatment on an arterial. Although general guidelines can be provided on where signal priority may be effective, each location warrants a separate analysis, similar to the type of analyses performed in this research.

APPENDIX I
SIGNAL PRIORITY IMPLEMENTATION PROJECTS

Los Angeles [20, 1]

The Los Angeles Department of Transportation (LADOT) and the Los Angeles county Metropolitan Transportation Agency (MTA) implemented a transit priority system for buses along two major transit corridors in Los Angeles region. The system covers 210 intersections and uses 331 loop detectors with more than 150 transponders. The system interfaces with real-time traffic control system to calculate the bus travel time between the detector and downstream intersection and determine the amount of signal green time extension needed for buses to clear the intersection.

In addition to signal priority, other changes were made to the transit system [1]. The number of stops was reduced from a two-tenth mile minimum between stops to an eight-tenth-mile minimum. Low floor buses were introduced to make it easier for passengers to board and exit the bus. Signs were posted to encourage passengers to exit in the rear. Drivers also instructed to do so. Overall benefits from all these changes were a 20-27% reduction in travel time. Benefit due to signal priority has been estimated (subjectively) to be 30 to 40% of this reduction. The adverse impacts on cross street traffic were minimal.

The system was implemented in three phases:

- Phase 1 - Test, design, and implement the hardware and software for the detection of the transit buses for the first 35 intersections.

- Phase 2 – Develop a smart feature so that priority is provided to a particular bus only if it is late.

- Phase 3 – Combine phase 1 and phase 2 to give priority on a network-wide basis.

LADOT conducted a field evaluation of 3 different technologies for vehicle detection to permit transit priority treatments at signals: infra-red beacon system, loop transponder detection (LTD) system, and radio-frequency antenna-transponder detection system. LTD was selected because of ease of installation and capital and maintenance costs. Transponders are mounted on the underside of the bus that communicates the bus ID with an inductive loop.

The system uses model 2070 traffic signal controller developed by LADOT and Caltrans. Types of priority include: Early green or red truncation, green extension, free hold, and phase call.

Maryland [14]

TSP was implemented in the MTA # 210 express bus system with green extension and queue jump. The system is in operation between MD 100 and US 50 and includes 12 signalized intersections. Green extensions were used where the busses passes through an intersection without picking the passengers. A queue jump was used where the bus stops at the near side of the intersection. Phase re-service was used at locations where a bus makes a left turn off an arterial to serve a park and ride lot. Phase re-service is when the left turn movement is serviced twice (if necessary) to enable a bus to make the turn into the parking lot. Gifford et al.[14] cites a 1999 report (Hood, 1999, unpublished) that indicates a 15 to 18% reduction in travel time along the route after implementation of TSP, with very little impact on the signal coordination.

Bremerton, Washington[14]

A 1993 study of Kitsap transit examined Opticom priority control for busses. The TSP System was technologically and functionally identical to the Opticom preemption system used for fire and emergency vehicles. The drivers controlled the device and some bus drivers said they felt that other drivers overused or improperly used the device. Also drivers differed in their use of the confirmation light. The drivers also noted that due to the way Opticom had been installed, there appeared to be substantial variation in where, when, and how the system could be triggered from intersection to intersection. The drivers found this disconcerting.

The fire department used the same system but calls for emergency vehicles were given absolute priority over transit vehicle calls. The study found that as a result of the TSP system, the average rider saved 5 minutes on a 49-minute trip.

Shoreline, Washington [12]

This was a simulation study that used VISSIM. It evaluated different types of transit priority. However, all the types included TSP, and hence, it is difficult to isolate the individual effect of TSP from the results.

The measures of effectiveness included travel speed, schedule reliability, and transit capacity.

Transit only lanes provided the greatest transit benefit by removing buses from congestion in the general purpose travel lanes. Transit queue by-pass lanes also produced substantial benefits. The length of the through queue at a signalized intersection influenced the effectiveness of these lanes. Using far side stops with queue by-pass lanes appeared to reduce delay associated with buses being ‘trapped’ in the near side bus bay when queues form at a downstream signal.

When compared to the no-build alternative, transit queue by-pass lanes increased transit speeds by 4.3 mph (55%). A substantially higher benefit was observed with the transit only lane where the speed more than doubled with an increase of 9.0 mph (115%). There were similar improvements in transit reliability.

PEEK LMD9200 firmware running on a NEMA signal controller was emulated in VISSIM at each signalized intersection. A green extension or red truncation strategy was used. There was no skipping of phases.

Short way offset seeking was used to transition back to normal settings. In this method, if adding time is necessary, one second is added for every five seconds of cycle time until synchronization is achieved. If subtracting time is necessary, every 5th second is removed until synchronization is achieved. It was agreed that the transit priority system cannot reduce green time for all other movements by more than 20% of the cycle length.

Toronto and Ontario, Canada [(21)]

Transit priority was implemented at 36 intersections for a light rail line in Toronto’s downtown core. Streetcar detection system includes two antennas embedded in the pavement. The first antenna located upstream of the transit stop is used to request transit priority. A transponder onboard the streetcar transmits a signal to the antenna. This antenna relays the request for priority to the local controller and ‘checks-in’ the streetcar into the system. The second antenna is embedded in the pavement immediately after the stop bar. The signal from this antenna is transmitted to the local controller to indicate that the streetcar has left the intersection and ‘checks-out’ the vehicle from the TSP system.

For this project, for the transit vehicles at major/minor intersections, there was an extension of the main street green or truncation of the side street green. At major/major intersections extensions are provided for all approaches with transit vehicles.

Extensions are provided in 1-second increments from a minimum of 3 seconds until either the transit vehicle clears the intersections or a predetermined maximum green extension duration is reached. The maximum green extension provided by transit priority is 30 seconds, depending on the location.

A statistical before-after study was not conducted. However, based on observations by staff, route travel times were reduced enough to remove one streetcar from the route, while maintaining the same quality of service.

At locations with near-side transit stops and large variations in dwell times, the benefits of transit priority is reduced. With near-side stops, when green extensions reach their maximum and the street car has not cleared the intersection, the priority can actually delay the street car (e.g., takes longer to return to main street green). Further, there were some complaints concerning increased pedestrian delays where transit priority has been implemented.

Route 123 project – Vancouver, British Columbia [21]

The purpose of this project was the demonstration of automatic vehicle location (AVL) and TSP technologies along a regional bus route. The scope of the project encompassed the equipping of 12 buses with vehicle location monitoring and signal preemption capabilities complemented by 10 intersections capable of being pre-empted by the buses.

NOVAX's Selective Detection System (SDS) was used.

Each intersection approach was equipped with two infra-red receivers, one 80 to 120m upstream of the intersection to mark the beginning of the preemption zone (check-in) and the second at the intersection to mark the end of the preemption zone (check-out) and clearance of the bus.

The vehicle system for the 12 busses in the demonstration project comprised of two components:
(1) An AVL system performing the vehicle location and schedule adherence monitoring functions
(2) A TSP component providing the bus mounted transmitters required for the roadside system detection equipment

The active strategies supported in this demonstration project comprised of green extensions and red truncations.

Travel time and trip time reliability data were reviewed to determine if the provision of transit priority at signals resulted in a reduction in travel times and/or in the variance of the travel times. Only marginal differences were observed in the average end-to-end travel time along the Route 123 corridor. Reductions in travel time variance was observed:
A 29% reduction in travel time variance was observed in the AM peak average travel times
A 59% reduction in travel time variance was observed in the PM peak average travel times

It terms of schedule adherence, results were inconclusive.

Portland [22]

The current undertaken by the City of Portland and Tri-Met has been implemented uses a 170 HC11 traffic controller, which is an evolutionary piece of hardware, as part of an eventual upgrade to a 2070-like Advanced Traffic Controller (ATC). The implementation allows green extension for the bus phase and red truncation when in a non-bus phase(s) while also maintaining coordination. The detection system used for the project was the 3M Opticom system, and an automatic vehicle location system to control the emitter.

The first phase of the project involved implementation of Route 104 – Division and Route 4 – Fessenden in Portland. The bus priority system has been implemented at 58 of the 72 intersections on Route 4 and 104. Early results have shown that improvements in travel time typically range from 5 to 8% of the overall travel time.

London [23]

The AVL system in London locates the buses using microwave beacons at the roadside supplemented by an odometer on each bus. Buses communicate with the central AVL system using Band III radio.

Different evaluations were conducted.

Simulation analysis indicated that maximum benefits for passengers waiting at bus stops occur when around 40% of buses with the highest headways are given priority, thus maximizing regularity improvements. The overall result (waiting time and travel time savings) indicate that benefits are maximized when between 40% and 100% of buses receive priority. Other tests incorporating greater variability in priority levels have indicated that benefits are maximized when 50% of buses receive priority.

Seattle [1]

The King County DOT in Seattle implemented signal priority in the 2.1 mile Rainier Avenue System (activated in the Spring of 2000), which includes nine intersections, five with priority. The hardware for the system included the Amtech RF (radio frequency) tags on the buses, Amtech log periodic antennas on the road, and the Transit Priority Request Generator. The controller system is made up of Eagle PEEK LMD 9600, and Econolite controllers.

Extension of green time and red time were possible. Results indicated that the AM peak period along Rainier Avenue experienced a 2.3 second / vehicle (13%) reduction in average intersection delay. Before and after studies conducted by King County Metro showed that TSP reduced the average intersection delay by approximately 5 seconds per TSP-equipped intersection – a reduction of 24% to 34% for TSP-eligible buses. In addition, intersection bus delay was reduced by an average of 34% when a bus was eligible for priority treatment.

APPENDIX II
Description of WATSim©

KLD Associates was responsible for the development of many of the traffic simulation models used in the industry, including most of the traffic simulation models sponsored by the U.S. Federal Highway Administration (FHWA). Of these models, the TRAF-NETSIM© model of urban street systems developed by KLD became FHWA’s most popular traffic simulation model. This model received 25 years of continuous support and development from the FHWA, and was extensively validated and used by hundreds of agencies world wide.

WATSim© Features

KLD’s WATSim© model is a direct and significant extension of TRAF-NETSIM© and provides an integrated simulation of freeways and surface streets at microscopic detail. Virtually *any* roadway system can be modeled with WATSim© including freeways, ramps, interchanges, surface streets, toll plazas, parking lots, gas stations, and airport circulation, and terminal curbside roadways. This "intelligent software" distinguishes between freeway and surface street roadways and automatically applies car-following and lane-changing logic appropriate to each environment. This is accomplished in a seamless fashion completely invisible to the user.

Unlike TRAF-NETSIM©, WATSim© also represents the operating characteristics of both heavy rail and light rail transit (LRT). The model can be used to study the operation of busy railroad grade crossings and the interaction of trains with other traffic. It can also model LRT operations along exclusive guide ways and on at-grade sections where rail traffic interacts with general traffic and pedestrians. In either case, the effects of transit preferential signaling can be studied. The model provides a realistic simulation of the traffic environment and provides statistical "Measures of Effectiveness" (MOE) which separately quantify traffic operations for bus and LRT vehicles as well as for the mix of general traffic and transit vehicles. Transit statistics include running times, number of trips, transit station statistics such as bus dwell times, area-wide and section specific transit statistics and electrical power consumption by route in the case of LRT simulations. An animation of simulated traffic and transit operations is also provided.

WATSim© Operating Characteristics

WATSim© is a time-based simulation model. Each vehicle in the traffic stream is represented as a distinct entity which is "moved" once each second accounting for the current traffic conditions. Vehicle trajectories are computed according to car-following and lane-changing logic that responds to the performance of neighboring vehicles, traffic control devices, and other conditions which influence driver behavior. These responses reflect both the performance capabilities of the individual vehicle and the relative "aggressiveness" or "timidity" of the simulated motorist. Typical conditions of an urban environment are represented including: double parked cars; unloading trucks; buses, and LRTs servicing passengers at stations; pedestrian interference with turning vehicles; and disruptions to traffic flow caused by vehicles pulling in and out of parking spaces along the curb.

Each simulated vehicle has its own performance capabilities and is “driven” by a simulated motorist exhibiting distinct behavioral characteristics. A set of 10 distinct “drivers” is employed in the simulation representing the entire range of driver personalities. The driver’s personality is used by the simulation model to compute an extensive number of driver decisions including:

Desired travel speed along each section of roadway;
Motivation to initiate a lane change;
Size of gap in adjacent lane that driver is willing to accept to make a lane change;
Whether or not to cooperate with another driver attempting a lane change in front;
Which gap in the oncoming traffic stream is acceptable to make an opposed left turn;
Acceptable gap to perform a right-turn-on-red maneuver;
Acceptable gap to proceed at STOP signs;
Acceptable gap to proceed at YIELD signs;
Whether or not to stop during a yellow signal indication;
Reaction time and start-up loss time for first driver in queue when signal changes from RED to GREEN;
Queue discharge headway (rate that driver in queue proceeds to discharge).

Each vehicle is also identified by category (car, HOV, bus, LRT, and truck). For example, trucks, buses, LRTs and HOVs can be restricted to specific lanes. An individual vehicle is further characterized by type of car, bus, etc. reflecting specific operational and performance characteristics. A fleet of 16 different “types” of vehicles can be specified to the model including 5 different types of rail cars.

The output of the model includes a variety of measures of effectiveness describing traffic operational performance. These include speed, volume, delay, spillback, and queues. Fuel consumption and pollutant emission measures are also provided. Traffic performance measures are available for each network link, each intersection, groups of links and the entire network over user-specified time intervals. Measures of transit operations are available by route and station.

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Table 1.1.1. Broad Street Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Existing Volumes in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	42	30.8	446.1	357.6	6
SB	46	34.4	400	311.1	6.7
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	1407	1041.36	228.3	139.5	11.7
SB	1743	1289.74	194.2	105.4	13.7

Table 1.1.2. Broad Street Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Existing Volumes in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	42	31.1	394.8	305.3	6.7
SB	47	34.8	363.1	274.6	7.3
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	1411	1044.48	204.8	116.0	13
SB	1748	1293.92	186.7	97.9	14.3

Table 1.1.3. Broad Street Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Existing Volumes in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	41	30.4	462.2	378.5	5.8
SB	40	29.9	458.3	365.6	5.8
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	1793	1327.21	213	124.2	12.5
SB	2184	1616.62	225.9	137.1	11.8

Table 1.1.4. Broad Street Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Existing Volumes in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	41	30.6	371.9	285.4	7.2
SB	40	29.9	426.8	334.4	6.2
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	1803	1334.47	187.2	98.3	14.2
SB	2204	1631.27	215.1	126.2	12.4

Table 1.2.1. Market Street Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Existing Volumes in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	44	26	347.7	275.3	6.1
EB	45	26.5	380	288.6	5.6
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	703	415.7	216.7	145.9	9.8
EB	900	531.86	177.6	106.7	12

Table 1.2.2. Market Street Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Existing Volumes in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	44	25.9	353.4	283.2	6
EB	45	26.7	438.5	345.6	4.9
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	703	415.62	229.4	158.6	9.3
EB	874	516.65	268.8	198.0	7.9

Table 1.2.3. Market Street Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Existing Volumes in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	35	20.8	308.4	238.5	6.9
EB	31	18.6	336.2	241.4	6.3
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	840	496.07	189.8	118.8	11.2
EB	891	526.75	177.6	106.7	12

Table 1.2.4. Market Street Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Existing Volumes in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	35	20.8	331.1	261.6	6.4
EB	31	18.6	336.2	241	6.3
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	836	494.27	204	133.2	10.4
EB	890	526.05	180.2	109.3	11.8

Table 1.3.1. Raymond Blvd Traffic Statistics without Transit Priority using Existing Signal Timing and Existing Volumes in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	15	7.1	256.9	171.1	6.7
EB	23	10.8	292.1	279	5.9
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	877	419.1	174.1	116.7	9.9
EB	895	427.52	242.9	185.5	7.1

Table 1.3.2. Raymond Blvd Traffic Statistics with Transit Priority using Existing Signal Timing and Existing Volumes in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	15	7.1	236.9	153.7	7.3
EB	23	10.8	313.3	315.5	5.5
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	877	419.09	156.7	99.3	11
EB	888	424.36	288.5	231.2	6

Table 1.3.3. Raymond Blvd Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Existing Volumes in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	15	6.9	453.6	322.4	3.8
EB	21	9.9	265	264.5	6.5
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	993	474.51	329.9	272.5	5.2
EB	482	230.27	228.7	171.3	7.5

Table 1.3.4. Raymond Blvd Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Existing Volumes in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	15	7.1	453.2	319.6	3.8
EB	21	10	248.7	240.3	6.9
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	972	464.46	368.2	310.8	4.7
EB	486	232.24	195.5	138.2	8.8

Table 2.1.1. Broad Street Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Future Volumes (+10%) in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	46	33.8	451.6	366.3	5.9
SB	51	37.5	410.4	321	6.5
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	1542	1140.98	239.1	150.2	11.1
SB	1919	1420.21	204.4	115.5	13

Table 2.1.2. Broad Street Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Future Volumes (+10%) in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	46	34.4	393.9	305.5	6.8
SB	51	37.7	377.5	287.7	7.1
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	1554	1150.09	217.8	129.0	12.2
SB	1912	1415.48	196.2	107.4	13.6

Table 2.1.3. Broad Street Traffic Statistics without Transit Priority using Existing Signal Timing and Future Volumes (+10%) in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	44	32.6	536.7	451.6	5
SB	42	30.8	481.2	385.6	5.5
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	1945	1439.26	229.6	140.7	11.6
SB	2349	1738.58	271.6	182.8	9.8

Table 2.1.4. Broad Street Traffic Statistics with Transit Priority using Existing Signal Timing and Future Volumes (+10%) in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	45	33.2	387.3	300.2	6.9
SB	42	31.4	413.4	323.9	6.4
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	1946	1440.04	190.3	101.5	14
SB	2446	1810.57	225.3	136.5	11.8

Table 2.2.1. Market Street Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Future Volumes (+10%) in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	46	27	372.4	300.8	5.7
EB	49	28.7	453.1	356.6	4.7
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	750	443.3	299.6	228.7	7.1
EB	977	577.19	217.5	146.6	9.8

Table 2.2.2. Market Street Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Future Volumes (+10%) in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	45	26.3	472.4	403.4	4.5
EB	42	25.1	621.1	502.3	3.4
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	744	439.65	374.6	303.7	5.7
EB	881	520.63	365.3	294.4	5.8

Table 2.2.3. Market Street Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Future Volumes (+10%) in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	44	25.8	363.6	295.5	5.9
EB	35	20.8	341.3	244.7	6.2
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	935	552.51	223.8	152.9	9.5
EB	976	576.71	182.2	111.3	11.7

Table 2.2.4. Market Street Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Future Volumes (+10%) in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	42	24.9	428.6	369	5
EB	35	20.9	425.6	318.2	5
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	919	543.3	294.1	223.3	7.2
EB	974	575.45	237.2	166.3	9

Table 2.3.1. Raymond Blvd Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Future Volumes (+10%) in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	17	8.2	279.5	188.7	6.2
EB	24	11.5	331.1	339	5.2
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	957	457.08	208.7	151.3	8.2
EB	886	423.19	312.8	255.3	5.5

Table 2.3.2. Raymond Blvd Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Future Volumes (+10%) in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	17	8.2	281.5	199	6.1
EB	25	11.8	381.3	379.7	4.5
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	959	458.1	193.2	135.8	8.9
EB	915	437.24	331	273.6	5.2

Table 2.3.3. Raymond Blvd Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Future Volumes (+10%) in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	15	7.3	557.5	382.7	3.1
EB	21	10.1	311.8	348.5	5.5
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	1022	488.15	408	350.5	4.2
EB	539	257.57	261.6	204.3	6.6

Table 2.3.4. Raymond Blvd Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Future Volumes (+10%) in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	15	7.3	485.5	331.5	3.5
EB	21	10.1	272.5	311	6.3
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	1075	513.72	401.3	344.0	4.3
EB	530	253.15	277.5	220.1	6.2

Table 3.1.1. %Travel Time Change on NB Broad Street in AM Peak Hour Relative to the Base Case				
	Existing Base, without transit priority	Existing Base, with transit priority	Future (+10%), without transit priority	Future (+10%), with transit priority
Transit		-11.5	1.2	-11.7
Other		-10.3	4.7	-4.6

Table 3.1.2. %Travel Time Change on NB Broad Street in PM Peak Hour Relative to the Base Case				
	Existing Base, without transit priority	Existing Base, with transit priority	Future (+10%), without transit priority	Future (+10%), with transit priority
Transit		-19.5	16.1	-16.2
Other		-12.1	7.8	-10.7

Table 3.1.3. %Travel Time Change on SB Broad Street in AM Peak Hour Relative to the Base Case				
	Existing Base, without transit priority	Existing Base, with transit priority	Future (+10%), without transit priority	Future (+10%), with transit priority
Transit		-9.2	2.6	-5.6
Other		-3.9	5.3	1.0

Table 3.1.4. %Travel Time Change on SB Broad Street in PM Peak Hour Relative to the Base Case				
	Existing Base, without transit priority	Existing Base, with transit priority	Future (+10%), without transit priority	Future (+10%), with transit priority
Transit		-6.9	5.0	-9.8
Other		-4.8	20.2	-0.3

Table 3.2.1. %Travel Time Change on EB Market Street in AM Peak Hour Relative to the Base Case				
	Existing Base, without transit priority	Existing Base, with transit priority	Future (+10%), without transit priority	Future (+10%), with transit priority
Transit		15.4	19.2	63.4
Other		51.4	22.5	105.7

Table 3.2.2. %Travel Time Change on EB Market Street in PM Peak Hour Relative to the Base Case				
	Existing Base, without transit priority	Existing Base, with transit priority	Future (+10%), without transit priority	Future (+10%), with transit priority
Transit		0.0	1.5	26.6
Other		1.5	2.6	33.6

Table 3.2.3. %Travel Time Change on WB Market Street in AM Peak Hour Relative to the Base Case				
	Existing Base, without transit priority	Existing Base, with transit priority	Future (+10%), without transit priority	Future (+10%), with transit priority
Transit		1.6	7.1	35.9
Other		5.9	38.3	72.9

Table 3.2.4. %Travel Time Change on WB Market Street in PM Peak Hour Relative to the Base Case				
	Existing Base, without transit priority	Existing Base, with transit priority	Future (+10%), without transit priority	Future (+10%), with transit priority
Transit		7.4	17.9	39.0
Other		7.5	17.9	55.0

Table 3.3.1. %Travel Time Change on EB Raymond Blvd in AM Peak Hour Relative to the Base Case				
	Existing Base, without transit priority	Existing Base, with transit priority	Future (+10%), without transit priority	Future (+10%), with transit priority
Transit		7.3	13.4	30.5
Other		18.8	28.8	36.3

Table 3.3.2. %Travel Time Change on EB Raymond Blvd in PM Peak Hour Relative to the Base Case				
	Existing Base, without transit priority	Existing Base, with transit priority	Future (+10%), without transit priority	Future (+10%), with transit priority
Transit		-6.2	17.7	2.8
Other		-14.5	14.4	21.3

Table 3.3.3. %Travel Time Change on WB Raymond Blvd in AM Peak Hour Relative to the Base Case				
	Existing Base, without transit priority	Existing Base, with transit priority	Future (+10%), without transit priority	Future (+10%), with transit priority
Transit		-7.8	8.8	9.6
Other		-10.0	19.9	11.0

Table 3.3.4. %Travel Time Change on WB Raymond Blvd in PM Peak Hour Relative to the Base Case				
	Existing Base, without transit priority	Existing Base, with transit priority	Future (+10%), without transit priority	Future (+10%), with transit priority
Transit		-0.1	22.9	7.0
Other		11.6	23.7	21.6

Table 4.1.1. Broad Street Traffic Statistics <u>without</u> Transit Priority using KLD Signal Timing and Existing Volumes in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	41	30.7	369.5	278.9	7.2
SB	48	35.8	363.6	275.3	7.3
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	1391	1029.51	189.8	101.0	14
SB	1760	1303.03	159.4	70.6	16.7

Table 4.1.2. Broad Street Traffic Statistics <u>with</u> Transit Priority using KLD Signal Timing and Existing Volumes in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	41	30.6	353.6	265.6	7.5
SB	46	34.2	353.8	262.5	7.5
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	1409	1042.86	184	95.2	14.5
SB	1750	1295.58	158.1	69.3	16.9

Table 4.1.3. Broad Street Traffic Statistics <u>without</u> Transit Priority using KLD Signal Timing and Existing Volumes in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	40	30	371	281.9	7.2
SB	40	29.5	370.3	279.7	7.2
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	1761	1303.53	187	98.2	14.3
SB	2014	1490.85	172.1	83.3	15.5

Table 4.1.4. Broad Street Traffic Statistics <u>with</u> Transit Priority using KLD Signal Timing and Existing Volumes in the PM Peak Hour**					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	42	30.8	358.2	270.4	7.4
SB	39	28.8	358.1	269.1	7.4
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	1756	1299.83	177.9	89.1	15
SB	2000	1480.25	172.9	84.1	15.4

** No Priority at Broad and Market Street

Table 4.1.5. Broad Street Traffic Statistics <u>with</u> Transit Priority using KLD Signal Timing and Existing Volumes in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	43	31.8	352.1	262.8	7.6
SB	40	29.8	368.7	280.1	7.2
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	1752	1296.53	175.2	86.37	15.2
SB	2015	1491.09	170.6	81.74	15.6

Table 4.2.1. Market Street Traffic Statistics <u>without</u> Transit Priority using KLD Signal Timing and Existing Volumes in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	43	25.7	338.6	268.3	6.3
EB	45	26.7	349.7	264.6	6.1
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	697	412.04	206.8	136.0	10.3
EB	906	535.2	179.5	108.5	11.9

Table 4.2.2. Market Street Traffic Statistics <u>with</u> Transit Priority using KLD Signal Timing and Existing Volumes in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	42	25	357.6	288.8	5.9
EB	43	25.4	504.3	401.9	4.2
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	688	406.55	377.8	306.9	5.6
EB	962	568.66	247.8	176.9	8.6

Table 4.2.3. Market Street Traffic Statistics <u>without</u> Transit Priority using KLD Signal Timing and Existing Volumes in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	36	21.3	372.5	305.5	5.7
EB	32	18.6	330.5	234.5	6.4
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	848	501.01	219.5	148.6	9.7
EB	891	526.47	178.4	107.5	11.9

Table 4.2.4. Market Street Traffic Statistics <u>with</u> Transit Priority using KLD Signal Timing and Existing Volumes in the PM Peak Hour**					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	35	20.9	329	261.8	6.5
EB	31	18.3	358.6	260	5.9
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	851	502.71	205	134.0	10.4
EB	890	525.66	191	120.1	11.1

** No Priority at Broad and Market Street

Table 4.2.5. Market Street Traffic Statistics <u>with</u> Transit Priority using KLD Signal Timing and Existing Volumes in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	28	16.8	441.2	384.5	4.8
EB	28	16.4	518.2	387	4.1
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	684	404.43	530.6	460	4.0
EB	795	469.59	355.5	284.4	6.0

Table 4.3.1. Raymond Blvd Traffic Statistics <u>without</u> Transit Priority using KLD Signal Timing and Existing Volumes in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	14	6.8	230	158.2	7.5
EB	23	11.1	321.5	312	5.4
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	883	421.84	153	95.7	11.2
EB	873	417.02	245.4	188.0	7

Table 4.3.2. Raymond Blvd Traffic Statistics <u>with</u> Transit Priority using KLD Signal Timing and Existing Volumes in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	16	7.5	267.1	187	6.4
EB	20	9.7	335.5	346	5.1
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	877	419.29	182.4	125.1	9.4
EB	843	403.02	296.9	239.7	5.8

Table 4.3.3. Raymond Blvd Traffic Statistics without Transit Priority using KLD Signal Timing and Existing Volumes in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	14	6.5	497	359.4	3.5
EB	19	9.3	209.7	197.3	8.2
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	1034	494.15	350.2	292.9	4.9
EB	495	236.66	130.8	73.5	13.2

Table 4.3.4. Raymond Blvd Traffic Statistics with Transit Priority using KLD Signal Timing and Existing Volumes in the PM Peak Hour**					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	15	7.4	440.5	336.7	3.9
EB	19	9.3	212.8	196.4	8.1
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	1035	494.44	337.8	280.4	5.1
EB	496	237.18	139.8	82.5	12.3

** No Priority at Broad and Market Street

Table 4.3.5. Raymond Blvd Traffic Statistics with Transit Priority using KLD Signal Timing and Existing Volumes in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	15	7.2	440.5	327.3	3.9
EB	20	9.5	238.7	226	7.2
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	972	464.54	376.7	319.4	4.6
EB	489	233.68	160.4	103.1	10.7

Table 5.1.1. %Travel Time Change for NB Broad Street Relative to Base Case in AM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		-11.5
	Other		-10.3
KLD Signalization and Existing Volumes	Transit	-17.2	-20.7
	Other	-16.9	-19.4

Table 5.1.2. %Travel Time Change for NB Broad Street Relative to Base Case in PM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		-19.5
	Other		-12.1
KLD Signalization and Existing Volumes	Transit	-19.7	-22.5**
	Other	-12.2	-16.5**

** No Priority at Broad and Market Street

Table 5.1.3. %Travel Time Change for SB Broad Street Relative to Base Case in AM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		-9.2
	Other		-3.9
KLD Signalization and Existing Volumes	Transit	-9.1	-11.6
	Other	-17.9	-18.6

Table 5.1.4. %Travel Time Change for NB Broad Street Relative to Base Case in PM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		-6.9
	Other		-4.8
KLD Signalization and Existing Volumes	Transit	-19.2	-21.9**
	Other	-23.8	-23.5**

Table 5.2.1. %Travel Time Change for EB Market Street Relative to Base Case in AM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		15.4
	Other		51.4
KLD Signalization and Existing Volumes	Transit	-8.0	32.7
	Other	1.1	68.1

Table 5.2.2. %Travel Time Change for EB Market Street Relative to Base Case in PM Peak Period			
		No Priority	Priority**
Existing Signalization and Existing Volumes	Transit		0.0
	Other		1.5
KLD Signalization and Existing Volumes	Transit	-1.7	6.7**
	Other	0.5	7.5**

** No Priority at Broad and Market Street

Table 5.2.3. %Travel Time Change for WB Market Street Relative to Base Case in AM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		1.6
	Other		5.9
KLD Signalization and Existing Volumes	Transit	-2.6	2.8
	Other	-4.6	14.4

Table 5.2.4. %Travel Time Change for WB Market Street Relative to Base Case in PM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		7.4
	Other		7.5
KLD Signalization and Existing Volumes	Transit	20.8	6.7**
	Other	15.6	8.0**

Table 5.3.1. %Travel Time Change for EB Raymond Blvd Relative to Base Case in AM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		7.3
	Other		18.8
KLD Signalization and Existing Volumes	Transit	10.1	14.9
	Other	1.0	22.2

Table 5.3.2. %Travel Time Change for EB Raymond Blvd Relative to Base Case in PM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		-6.2
	Other		-14.5
KLD Signalization and Existing Volumes	Transit	-20.9	-19.7**
	Other	-42.8	-38.9**

** No Priority at Broad and Market Street

Table 5.3.3. %Travel Time Change for WB Raymond Blvd Relative to Base Case in AM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		-7.8
	Other		-10.0
KLD Signalization and Existing Volumes	Transit	-10.5	4.0
	Other	-12.1	4.8

Table 5.3.4. %Travel Time Change for WB Raymond Blvd Relative to Base Case in PM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		-0.1
	Other		11.6
KLD Signalization and Existing Volumes	Transit	9.6	-2.9**
	Other	6.2	2.4**

** No Priority at Broad and Market Street

Table 6.1.1. %Travel Time Change for NB Broad Street Relative to Base Case in PM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		-19.5
	Other		-12.1
KLD Signalization and Existing Volumes	Transit	-19.7	-23.8
	Other	-12.2	-17.7

Table 6.1.2. %Travel Time Change for SB Broad Street Relative to Base Case in PM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		-6.9
	Other		-4.8
KLD Signalization and Existing Volumes	Transit	-19.2	-19.6
	Other	-23.8	-24.5

Table 6.2.1. %Travel Time Change for EB Market Street Relative to Base Case in PM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		0.0
	Other		1.5
KLD Signalization and Existing Volumes	Transit	-1.7	54.1
	Other	0.5	100.2

Table 6.2.2. %Travel Time Change for WB Market Street Relative to Base Case in PM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		7.4
	Other		7.5
KLD Signalization and Existing Volumes	Transit	20.8	43.1
	Other	15.6	179.6

Table 6.3.1. %Travel Time Change for EB Raymond Blvd Relative to Base Case in PM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		-6.2
	Other		-14.5
KLD Signalization and Existing Volumes	Transit	-20.9	-9.9
	Other	-42.8	-29.9

Table 6.3.2. %Travel Time Change for WB Raymond Blvd Relative to Base Case in PM Peak Period			
		No Priority	Priority
Existing Signalization and Existing Volumes	Transit		-0.1
	Other		11.6
KLD Signalization and Existing Volumes	Transit	9.6	-3.0
	Other	6.2	14.2

Table 7.1.1. Broad Street Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Future Volumes (+20%) in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	49	36	477	389.9	5.6
SB	54	40.1	428.1	339.3	6.2
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	1673	1238.26	256.5	167.7	10.4
SB	2076	1536.79	222.3	133.5	12

Table 7.1.2. Broad Street Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Future Volumes (+20%) in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	49	36.4	430.4	340.2	6.2
SB	55	40.7	399.5	310.5	6.7
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	1675	1240.11	245.6	156.8	10.8
SB	2091	1547.95	208.6	119.8	12.8

Table 7.1.3. Broad Street Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Future Volumes (+20%) in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	48	35.7	608.4	526.6	4.4
SB	47	34.8	536.9	437.6	5
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	2099	1553.77	266.1	177.3	10
SB	2347	1736.82	351.4	262.5	7.6

Table 7.1.4. Broad Street Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Future Volumes (+20%) in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
NB	49	36	480.2	390.7	5.5
SB	47	35	500.3	399.5	5.3
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
NB	2118	1567.91	226.3	137.5	11.8
SB	2443	1807.91	350.2	261.3	7.6

Table 7.2.1. Market Street Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Future Volumes (+20%) in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	47	27.8	531.4	460.3	4
EB	52	30.5	521.2	414.7	4.1
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	775	458.14	468	397.3	4.5
EB	1036	612.29	258.1	187.2	8.2

Table 7.2.2. Market Street Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Future Volumes (+20%) in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	47	28	470.1	395.8	4.5
EB	51	30.2	510.7	407.2	4.2
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	687	406.14	534.6	463.9	4
EB	1028	607.29	272.3	201.3	7.8

Table 7.2.3. Market Street Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Future Volumes (+20%) in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	43	25.4	342.8	274.3	6.2
EB	37	21.9	376.5	275	5.6
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	1009	596.23	211	140.1	10.1
EB	1062	627.36	197.7	126.8	10.8

Table 7.2.4. Market Street Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Future Volumes (+20%) in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	43	25.4	347.3	278.7	6.1
EB	37	22.1	365.8	267.8	5.8
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	1008	595.6	222.7	151.7	9.6
EB	1065	629.27	193.3	122.3	11

Table 7.3.1. Raymond Blvd Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Future Volumes (+20%) in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	18	8.7	375.6	251.3	4.6
EB	22	10.4	352.6	418.2	4.9
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	998	476.99	301.1	243.8	5.7
EB	839	400.86	341.6	284.3	5

Table 7.3.2. Raymond Blvd Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Future Volumes (+20%) in the AM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	19	8.9	374.9	251.8	4.6
EB	24	11.7	343.6	370.5	5
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	985	470.47	305.1	247.6	5.6
EB	892	426.27	307.6	250.3	5.6

Table 7.3.3. Raymond Blvd Traffic Statistics <u>without</u> Transit Priority using Existing Signal Timing and Future Volumes (+20%) in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	17	8.2	564.6	392.4	3
EB	20	9.5	325.9	402.8	5.3
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	1040	497.01	408.8	351.5	4.2
EB	489	233.83	434.2	377.1	4

Table 7.3.4. Raymond Blvd Traffic Statistics <u>with</u> Transit Priority using Existing Signal Timing and Future Volumes (+20%) in the PM Peak Hour					
Bus Statistics					
Section	Bus Trips	Bus Miles	Mean Travel Time (sec/trip)	Mean Delay (sec/bus)	Avg. Speed (mph)
WB	17	8	564.5	399.9	3
EB	23	11.1	299.6	341.7	5.7
General Traffic Along Arterial Statistics					
Section	Vehicle Trips	Vehicle Miles	Mean Travel Time (sec/veh)	Mean Delay (sec/veh)	Avg. Speed (mph)
WB	1060	506.29	408	350.5	4.2
EB	556	265.74	350.5	293.2	4.9

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