An Evaluation of Transit Signal Priority and SCOOT Adaptive Signal Control

by

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ABSTRACT

Cities worldwide are faced with the challenge of improving transit service in urban areas using lower cost means. Transit signal priority is considered to be one of the most effective ways to improve the service of transit vehicles. Transit signal priority has become a very popular topic in transportation in the past 20 to 30 years and it has been implemented in many places around the world. In this thesis, transit signal priority strategies are categorized and an extensive literature review on past research on transit signal priority is conducted. Then a case study on Columbia Pike in Arlington (including 21 signalized intersections) is conducted to assess the impacts of integrating transit signal priority and SCOOT adaptive signal control. At the end of this thesis, an isolated intersection is designed to analyze the sensitivity of major parameters on performance of the network and transit vehicles.

The results of this study indicate that the prioritized vehicles usually benefit from any priority scheme considered. During the peak period, the simulations clearly indicate that these benefits are typically obtained at the expense of the general traffic. While buses experience reductions in delay, stops, fuel consumption, and emissions, the opposite typically occurs for the general traffic. Furthermore, since usually there are significantly more cars than buses, the negative impacts experienced by the general traffic during this period outweigh in most cases the benefits to the transit vehicles, thus yielding overall negative impacts for the various priority schemes considered. For the off-peak period, there are no apparent negative impacts, as there is more spare capacity to accommodate approaching transit vehicles at signalized intersections without significantly disrupting traffic operations.

It is also shown in this study that it is generally difficult to improve the system-wide performance by using transit priority when the signal is already optimized according to generally accepted traffic flow criteria. In this study it is also observed that the system-wide performance decreases rapidly when transit dwell time gets longer.

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1 INTRODUCTION

1.1 Need for Transit Signal Priority

Cities worldwide are faced with the challenge of improving transit service in urban areas using more cost effective alternatives. Transportation system management strategies have evolved over the years as potential cost effective alternatives as a result of the significant increase in travel demand in urban areas, lack of additional land to expand the transportation system, and the increase in construction costs.

Obviously the efficiency of the existing transportation system can be improved if transportation management strategies are aimed at mass transit systems in addition to passenger car vehicles. If transit vehicles, with much higher ridership than passenger cars, are given priority in such strategies, the person throughput as well as the fuel efficiency of the system may increase significantly. Thus, in recent years, the emphasis of urban traffic management policies has been shifting from the smooth movement of the entire system towards the discrimination between transit vehicles and private cars by providing transit vehicles priority strategies at signalized intersections. The goal of this shift is to improve the level of service of the mass transit system by accounting for the extra passengers that travel on a transit vehicle. This is also one of the reasons why transit signal priority is gaining more and more attention over the last two or three decades. Most on-site tests and studies show that transit signal priority is feasible under most conditions.

One of the major reasons for the inefficiency of the current urban transportation system is the delay experienced by high occupancy transit vehicles at signalized intersections. It was estimated that stopped delay at intersections comprises about 20 percent of the overall transit vehicle delays. With the rapid development of microprocessors and communication technologies, efforts have been devoted to developing traffic-responsive signal control methods to meet the ever-increasing traffic demand. Since conventional fixed time signal control design methods are based on the use of historic data, they cannot fully accommodate time-dependent flows. Actuated signal control systems have been developed to meet such changing demands. When demands vary and can be monitored in real time, actuated/demand-responsive signal control strategies have the potential to perform better than fixed-time control strategies, by employing the use of automatic vehicle detection technologies. Such detector-based technologies have been extended to identify particular vehicle types, like transit, and give priority to these vehicles over the rest of the traffic, to improve their performance and profitability. Such transit-oriented prioritized traffic operation at signalized intersections is achieved using signal priority techniques. Many studies and tests all over the world have shown that transit signal priority can reduce the travel time for passengers by up to 20 percent, with fewer stops and starts, and in most cases, without significant impact on general traffic flow and nominal delay to cross streets. The enhanced transit system operations has the potential to improve transit service levels, which may lead to increased transit ridership. Increased ridership is can result in fewer passenger cars, which in turn results in less fuel consumed and fewer vehicle emissions released into the atmosphere.

Transit signal priority is a technique of adjusting signal timings to accommodate transit vehicles in order to reduce the amount of stopped delay for targeted vehicles, like buses or emergency vehicles. Simply speaking, this technique gives the targeted vehicles some priority when these vehicles arrive at intersections. The level of priority can vary widely, and there are many different strategies to implement different levels of priority. The different priority strategies will be discussed later in Chapter 2 of the thesis.

In order to improve the attractiveness of transit to the public in general, buses are required to adhere to their schedule. Uncertainties in the time of passenger loading and unloading at bus stops make the exact prediction of bus arrival times at intersections very difficult. The location of bus stops (near side or far side) also affects the ability of buses to travel through the intersection in an uninterrupted manner. Hence, real time detection of transit vehicles is necessary to provide continuous green phases to the transit vehicles. The priority technology includes on-vehicle emitters, loops, sensing devices and tags, roadside beacons, GPS, automatic vehicle localization systems (AVL) and real-time traffic control system that can detect an approaching bus, predict its arrival time at the intersection and communicate the information to the signal controller for necessary action. The objective of such priority strategies is to increase the perceived advantage of transit relative to the single occupancy vehicles and therefore differentiate private automobiles from the transit vehicles.

Signal priority technology is used not only for transit vehicles but also for other special vehicles like fire engines, ambulances, police cars etc. In almost every emergency call-out for the services of such vehicles, dangerous situations arise, especially when crossing intersections and when using opposite lanes. These situations may lead to serious accidents, if not properly coordinated. In city/urban traffic, such a call-out requires the use of continuous sirens. Such emergency vehicles are usually exempt from the traffic regulations when they are fitted with sirens and flashing lights. But the use of sirens leads to an almost intolerable levels of noise pollution, especially if the frequency of these emergency vehicles is high. However, journey speeds of emergency vehicles have become lower as the traffic density has increased with cross street traffic impeding these journeys. Hence signal-setting strategies, to give priority to emergency vehicles, have become necessary to give unimpeded passage to these vehicles at signalized intersections and to stop all cross-street and opposing traffic. In chapter 2, some systems having the ability to provide priority to these special vehicles will be introduced.

Transit signal priority has been widely used in the US, Canada, Europe, Japan, and many other places around the world. It has been incorporated in many signal systems and is performing at different levels of success. At the same time, many research studies are currently underway to quantify the impacts of transit signal priority on the transportation system.

1.2 Goals, Objectives and Scope of Work

The goals of this thesis are two-fold. The first goal is to investigate the benefits of integrating adaptive signal control and transit signal priority. The evaluation of the integrated operation of adaptive signal control and transit signal priority is important given that adaptive signal control is becoming widely used in urban areas. The second goal of the study is to identify critical traffic, transit, and signal control parameters that impact the benefits of transit signal priority.

1.3 Thesis Contributions

This thesis makes two major contributions. First, the thesis presents a unique study of the interaction of transit signal priority and SCOOT adaptive signal control. Specifically, simulation and field tests were conducted to evaluate the potential benefits of using adaptive traffic signal control along busy arterials and to determine the potential benefits of integrating transit signal priority with adaptive signal control. Second, the thesis presents a unique systematic evaluation of transit signal priority to isolate critical traffic, network, transit, and signal control parameters on the potential benefits of transit signal priority.

1.4 Thesis Organization

This thesis is organized into six chapters including this introductory chapter. Following this chapter, chapter 2 reviews the vast work that has been performed on transit signal priority. This includes the often-used transit signal priority strategies, the effect of these strategies on the entire transportation system, and findings of other evaluation studies.

Chapter 3 introduces the main modeling task of the Columbia Pike model in the microscopic simulation software, INTEGRATION. This chapter describes the test corridor that was chosen for the simulation study, the study approach, the data collection efforts that were conducted to generate a simulation model of the test corridor, the various signal control strategies that were considered.

Following Chapter 3, chapter 4 presents the results of extensive simulations from the Columbia Pike study. The study includes both the peak-time analysis and off-peak time analysis. Conclusions based on this study are also presented.

In Chapter 5 an isolated intersection is designed to study the factors that influence the performances of both the transit vehicles and the system. These factors include bus arrival time during the cycle, number of phases in one cycle, traffic demand level, traffic demand distribution between the bus approach and crossing approach, cycle length, phase lengths, bus arrival approach, bus stop duration, and frequency of buses. This extensive sensitivity analysis is important in order to separate the influences of different factors on the potential system-wide impacts of transit signal priority.

Chapter 6 presents some general conclusions and provides recommendations for future research regarding transit priority.

2 LITERATURE REVIEW

A first step in evaluating transit signal priority, adaptive signal control, and the integration of transit signal priority with adaptive signal control is to review the state-of-the-art transit signal priority and adaptive signal control systems, evaluations, and findings of other studies.

This chapter first reviews the vast work that has been performed on evaluating transit signal priority. The chapter covers the often-used transit signal priority strategies, the effect of these strategies on the entire transportation system, and findings of other evaluation studies. Subsequently, the chapter describes a number of the current state-of-the-art and current state-of-the-practice adaptive traffic signal control systems. In addition, the chapter presents findings and results of other evaluation studies.

2.1 Overview of State-of-the-Art Transit Signal Priority Systems

Research on transit signal priority has been conducted worldwide over the past 20 to 30 years. Specifically, transit signal priority has been tested in various urban areas all over the United States. In addition, transit signal priority is widely used in Canada, Japan, and Europe. Vehicle signal priority includes light rail transit, express bus vehicles, and/or regular transit vehicles. In general, signal priority strategies can be classified into three categories: passive priority, active priority, and real-time priority strategies. Each category is introduced and described in the following sub-sections.

2.1.1 Passive priority strategies

Passive priority strategies attempt to favor roads with significant transit use in the area-wide traffic signal timing scheme by considering factors such as timing coordinated signals at the average transit vehicle speed instead of the average automobile speed, reducing the cycle length to reduce delay, providing phase sequence designed to more frequently serve a phase that has high transit demand, or by providing transit by-pass at metering locations. The commonly used passive priority strategies are listed below.

- Adjustment of cycle length

  Shortening the cycle lengths at intersections along transit routes helps reducing transit vehicle delay. But it also reduces the capacity of intersections. So, the benefits to transit vehicles from shortening cycle lengths must be weighed against the cost associated with the reduced capacity resulting from shorter cycle lengths.
- Phase splitting

  Phase splitting refers to splitting priority phases into multiple phases and repeating these phases within one cycle. In Figure 2.1, transit vehicles use phase A, which is split into two separated phases with the total time equal its original duration. Although the cycle length is not changed given that an intergreen interval is required at the end of each green interval, the capacity of the intersection is reduced by these strategies.

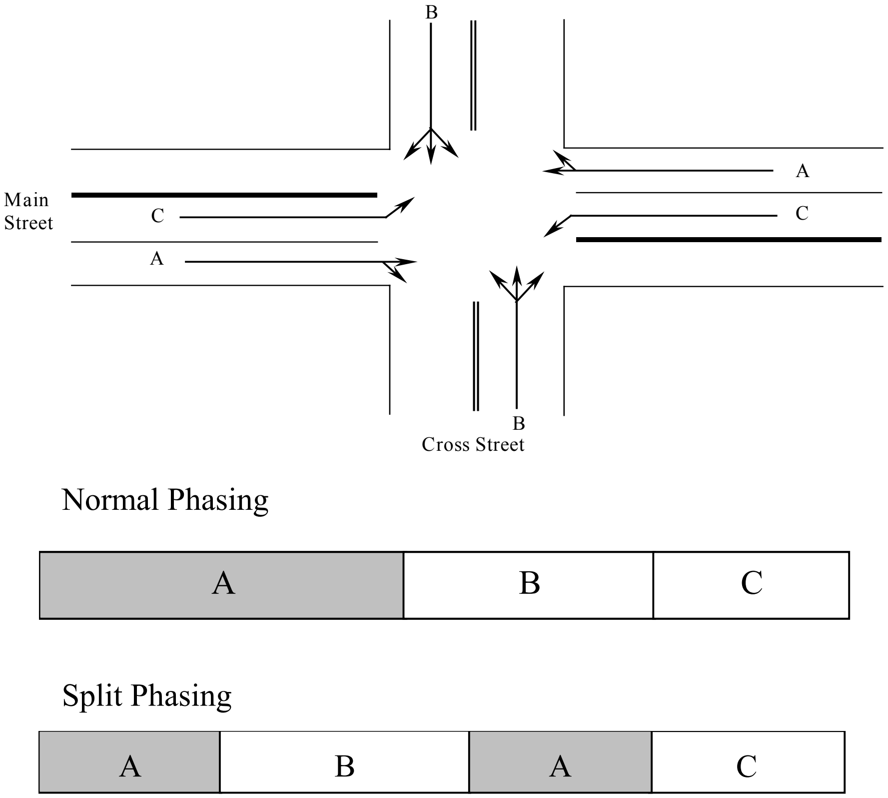

Figure 2.1: Illustration of phase splitting

- Area-wide timing plans

  Area-wide timing plans can be generated in two ways: They can be generated by allocating green time for each phase based on the number of passengers, rather than vehicles, which pass through the network intersections. To use this technique, vehicle occupancies must be known to allow average passenger delay to be minimized. Area-wide timing plans can also be designed to give priority to transit vehicles by coordinating intersection signal plans to allow for transit vehicle progression through the network. Because of the large variability in dwell times, the effectiveness of this technique is highly dependent on the ability to forecast the bus travel times between the network intersections. As a result, is best suited for express transit routes, because these routes are less prone to variability in travel times between intersections.
- Metering vehicles

  The flow of vehicles entering a designated roadway in a network can be restricted by metering a signal phase. This metering of flow reduces the flow downstream a bottleneck. Transit signal priority can allow transit vehicles to bypass the metered signal phases, thus providing a smoother flow for transit vehicles.

2.1.2 Active priority strategies

By contrast, active priority strategies involve detecting the presence of a transit vehicle, and depending on the system logic and the traffic conditions, provide special treatment for the transit vehicles. An active system must be able to both detect the presence of a bus and predict its arrival time at the intersection. Thus, a communication link between the traffic signal controller and the transit vehicles is needed to support active priority. As a result, initial capital investment as well as periodic maintenance costs is required to operate active priority strategies. The five commonly used active priority strategies are described in the following sub-sections.

- Phase extension (green extension)

  Additional green time is allocated to the end of the transit vehicle's normal green phase to allow it to pass through the intersection without stopping.
- Early start of a phase (red truncation)

  Additional green time is allocated to the beginning of the transit vehicle's normal green phase to reduce the delay incurred by the transit vehicle.
- Introduction of a special phase (red interruption)

  A short green phase on the transit vehicles' approach is inserted into its normal red phase while conflicting approaches are forced to stop.
- Phase suppression

  A low-volume non-priority phase is eliminated from the intersection signal timing plan.
- Green truncation

  If a transit vehicle is detected far from the intersection, truncating the transit vehicle's green as it is detected will increase the probability that the transit vehicle will receive a green during the next cycle as it arrives at the intersection. Delay to the cross street may be reduced through green truncation. With green truncation, the additional green given to the transit vehicle is truncated once the transit vehicle passes through the intersection.

Active priority measures can be grouped into two main categories: unconditional priority and conditional priority. In the former approach, a priority measure is granted whenever the transit vehicle calls for priority, subject to safety considerations including minimum clearance intervals. In the latter approach, transit signal priority is only granted if pre-defined conditions are satisfied, thus the term conditional priority. Typical conditions include the degree of saturation on approaches that will disbenefit from signal priority, transit vehicle schedule adherence, and/or transit vehicle ridership. Additional criteria include time since priority was last given at the intersection, the number of queued cross street vehicles, the status of the transit vehicle schedule or headway adherence, or constraints due to the road network's area-wide timing. Conditional priority is used more often at locations within a network of closely spaced traffic signals, because intersections do not operate independently in this environment. Therefore, the benefit to the network as a whole must be considered before priority is granted to a transit vehicle at a single intersection.

2.2 Overview of State-of-the-Art Adaptive Signal Control Systems

Real-time signal control systems attempt to provide transit priority based on optimizing some performance criterion, primarily delay. Delay measures may include passenger delay, vehicle delay, weighted vehicle delay or some combination of these measures. Real-time priority strategies use actual observed vehicle (both passenger and transit vehicle) arrivals as inputs to a traffic model that either evaluates several alternative timing plans to select a most favorable option, or optimizes the actual timing in terms of phase duration and phase sequence.

There are several well known real-time traffic responsive signal control systems that have been developed with the explicit objective of controlling traffic in urban signalized networks. SCOOT, UTOPIA, PRODYN, and SCATS are four of the most famous state-of-practice systems. These systems are briefly described.

2.2.1 SCOOT

SCOOT (Split Cycle Offset Optimization Technique) is a tool for managing and controlling traffic signals in urban areas that was developed in England [1]. It is adaptive and responds automatically to traffic fluctuations. SCOOT has proved to be an effective and efficient tool for managing traffic on signalized road networks and is now used in over 170 towns and cities in the UK and across the world. SCOOT uses data from vehicle detectors and optimizes traffic signal settings to reduce vehicle delays and stops. SCOOT began to provide transit priority in 1995. In SCOOT, buses can be detected either by selective vehicle detectors (SVD), i.e. using bus loops and bus-borne transponders, or by an automatic vehicle location (AVL) system.

The signal timings are optimized to benefit the buses by either extending a current green signal (an extension) or causing succeeding phases to occur early (a recall). Extensions can be awarded centrally, or the signal controller can be programmed to implement extensions locally on street (a local extension). SCOOT can be configured by node to allow or disallow each of these methods of priority. In principle recalls could also be awarded locally, but they are less critical and the extra programming of the controllers is not considered cost effective.

Extensions awarded in the controller can be advantageous as they eliminate 3 to 4 seconds of transmission delay from street to computer and back to street, and thus allow the system to grant extensions to buses which arrive in the last few seconds of green. This is especially important when link lengths are short, with bus stops often further restricting the effective link length. SCOOT is still in control as it sends a bit each second to permit local extensions only when the degree of saturation of the crossing street is sufficiently low.

Once the bus has passed through the signals, a period of recovery occurs to bring the timings back into line with the normal SCOOT optimization. Four methods of recovery are provided for operation after extensions and recalls, of which two methods (one for extensions and one for recalls) are recommended for normal use and operate by default.

The amount of priority given to buses can be restricted depending on the degree of saturation of the cross street as modeled by SCOOT. This is controlled by target degrees of saturation for extensions and recalls. These are the degrees of saturation to which the non-priority phases can be run in the case of a priority extension or recall respectively. Normally the target degree of saturations should be set so that the crossing street is not allowed to become oversaturated, although some degree of oversaturation may be allowed to service an extension. This means that bus priority will be most effective at crossing streets that have spare capacity.

The Bus SCOOT applications described above aim to reduce "phase delays" (due to buses arriving at an intersection on red), rather than the more significant delays that can occur to buses in congested conditions. SCOOT also uses “traffic metering” to manage congestion.

SCOOT uses traffic metering to allow traffic to be relocated away from one or more congested link within a network, onto one or more upstream links where it is more feasible to protect buses by physical bus priority, such as a bus lane. Typically, traffic metering is used to hold traffic outside of a town center to maintain free movement of vehicles in the central area. It is hoped that, in keeping internal, critical, links relatively free of congestion, the network becomes more stable with the following positive effects on public transport:

- Bus travel times become more reliable
- Buses will be able to enter links more easily
- Buses will be able to pull out from bus stops more easily
- Delay is reduced for buses

To implement traffic metering the traffic manager specifies each link to be metered (the metered link) and one or more bottleneck (trigger) links associated with the metered link. Metering is triggered whenever one of the bottleneck links reaches its pre-defined critical saturation level. The critical saturation level for a bottleneck link is usually determined according to its ability to store a queue without adversely affecting other upstream links. When metering is triggered the amount of green time allocated to the metered link is reduced by a few seconds every cycle until the saturation levels on all the bottleneck links are under their critical levels. When this occurs the metering action ends and normal SCOOT control takes place.

Traffic is allowed into the previously congested downstream link at a rate that the link can discharge. Buses are protected from the upstream queue by the bus lane. When the correct metering balance is achieved, transit times for buses through the network reduce, without imposing increased transit times on general traffic.

Trials in London showed that metering is most beneficial to general traffic where there is a substantial amount of cross-movement traffic flow, e.g. where north-south traffic conflicts with east-west traffic [2]. Conversely, metering is less effective on arterial roads where the large majority of traffic is traveling in the same direction. Public transport gains are most when the metered link(s) has/have a bus lane, allowing buses to bypass queues. Finally, benefits are maximized by restricting priority to late/long headway buses.

2.2.2 UTOPIA

UTOPIA (Urban Traffic Optimization by Integrated Automation) is a fully traffic responsive UTC system developed in Italy and its first implementation was carried out in Turin in 1985 [3]. It is designed with the twofold objective to (1) optimize private traffic control at the area level and, simultaneously (2) provide weighted and absolute priority for selected public transport vehicles. It mainly considers control of private vehicles together with a comprehensive public transport operation within a large scale, hierarchical decentralized traffic adaptive control system. Problems are classified into two levels, Intersection level (lower level) and Area level (decision level). The area level traffic model predicts O-D for passenger cars based on historical data and real-time information collected from local intersections. Then, a cost function considering delay to intersection traffic flow, public transit buses, and the entire study area decision policy is optimized at the local level. For the intersection level, UTOPIA could: (1) utilize its microscopic model to simulate traffic flow at a signal, and (2) determine the signal setting to get some traffic performance index such as vehicle delay to passenger cars and transit vehicles, vehicle stops, queue length, and deviation from signal setting decided in the previous iteration. For the area level, the model can: (1) analyze area-wide traffic data and make predictions for main street flows in time, (2) apply its internal macroscopic model to entire area network and traffic counts, and (3) optimize the total travel time with constraints of average speed and saturation flows.

Practical applications of the model have shown that the use of average link travel time from upstream detectors may directly impact system prediction validity and optimization performance. In addition, the reliability of O-D prediction is insufficient for practical uses.

A key component of the UTOPIA system developed in Turin is the SPOT intelligent signal control processor. This processor implements the "intersection level" control function of the UTOPIA system. Each intersection equipped with SPOT aims to minimize a set of cost functions over a rolling horizon of 120 seconds and cooperates with the neighboring intersections by exchanging information on the traffic observed and the control decided locally. The optimization and communication process is updated every three seconds. So the resulting optimal signal settings are actually in operation only for three seconds.

The elements considered in the cost function include time lost by vehicles on the incoming links, stops on the incoming links, time lost on the outgoing links by vehicles leaving the intersection, deviation from the reference plan provided by the central level, and deviation from the signal setting decided at the previous iteration. Transit vehicles are handled in terms of vehicle arrival time predictions and are represented as weighted platoons of private vehicles. Currently, absolute priority vehicles correspond to four-five hundred equivalent vehicles and the weight of normal priority vehicles depends on the weight predefined for the corresponding services.

The earliest version of UTOPIA was installed in Turin, Italy in 1985 and has been carefully assessed [4]. Independent field trials in 1985 and 1986 showed increases in average speed for public transport vehicles of 20% and a parallel increase of private traffic speed of 16%. Other field trials have shown that travel time reductions during rush hour were as high as 35% for public transport vehicles and 30% for private vehicles compared to fixed time plans.

2.2.3 PRODYN

PRODYN is a real-time traffic control system developed in France and implemented in three French cities. In 1998 a version of PRODYN specifically developed to provide priority to buses was developed for implementation in Toulouse [5]. PRODYN is based on state space modeling and estimation of queues, with signal control computations at each intersection performed on a 75 second rolling horizon every 5 seconds. Coordination is ensured by the exchange of platoon forecasts from upstream to downstream intersections.

Originally, transit priority in PRODYN was achieved in a non-optimal way by assuming a detected bus to be worth several private vehicles in the optimization process. However, a new process for transit priority in PRODYN was developed in the DRIVE II CITIES project and tested through simulation [6]. For each link, an estimation of priority vehicle state variables is performed at each sampling time using the values predicted at the previous sampling time and, for an internal link, the information received from the upstream intersection module. Predicted values are then modified according to actual bus detections. Optimization criteria include a consideration of the weighted priority vehicle delay and the probability of the vehicle having left the link.

In DRIVE II, evaluation of PRODYN indicated typical reductions in travel time of 10% with associated savings in fuel consumption and emissions.

2.2.4 SCATS

The SCATS (Sydney Coordinated Adaptive Traffic System) system was developed in the 1970’s by the Road and Traffic Authority of New South Wales, Australia [7]. SCATS is one of several forms of adaptive control that has the ability to change the phasing and timing strategies and the signal coordination within a network to meet changes in demand.

SCATS gathers data on traffic flows in real-time at each intersection. These data are transmitted via the traffic control signal box to a central computer. The computer makes incremental adjustments to traffic signal timings based on minute-by-minute changes in traffic flow at each intersection. SCATS performs a vehicle count at each stop line, and also measures the gap between vehicles as they pass through each intersection. As the gap between vehicles increases the traffic signal approach is wasting green time, and SCATS seeks to reallocate green time to where demand is greatest.

In a centralized system, SCATS adjusts signal plans based on traffic conditions at critical intersections. These critical intersections control coordination within subsystems and subsystems coordinate with other subsystems as traffic demands vary. Subsystems can include from one to ten intersections.

On detection of a bus approaching an intersection, priority phases can be called to either clear the queue ahead of the vehicle or to provide a phase extension. Flexibility is provided by allowing priority to be given or not depending on the time of day, tidal flow determination based on traffic flows, or on the level of congestion at the intersection approaches.

One report of the FAST-TRAC program in the Detroit area, which uses the SCATS adaptive signal control system, showed that travel time was reduced by 13.8%; delay reduction was 37.1%; and fuel consumption reduction was 5.5% [8].

2.3 Transit Signal Priority Evaluation Studies

Signal priority has been studied and tested in various urban areas around the United States. It has also been widely applied and studied in Canada, Japan, and Europe. In this section the results of the major studies are presented including the study findings and conclusions.

2.3.1 Field Tests in Louisiana Avenue/I394 interchange, Minnesota

The objectives of Louisiana Avenue project were to improve schedule adherence of buses and reduce operating costs [9]. This project is characterized by closely spaced intersections with significant turning volumes and frequent pedestrian activity. The primary performance measures included bus travel time, auto travel time and approach delay.

Three levels of priority were evaluated with comparison to the no priority base case. Low and medium priority used special priority phases that were called when buses were detected. These phases provided phase extensions to the normal phase times. The length of the phase splits assigned to the priority phases determined the difference between low and medium priority. The signal remained in coordination during the service of low and medium priority events. High priority was provided through the use of preemption.

The result showed that high priority strategy had a significant improvement in bus travel times (overall 38% reduction). Medium and low strategies showed no reduction in bus travel times. Low and medium priority strategies did not increase auto-stopped time and high priority strategy resulted in a 23% increase in delay. The investigator concluded that priority treatment within coordinate operation is a viable strategy.

2.3.2 Field Tests in Miami, FL

A field test was made along a 16-km section of the I-95 and Northwest Seventh Avenue corridor in Miami in 1973 [10]. Three bus priority strategies (a reversible, exclusive bus lane, signal preemption for buses, and a coordinated signal system with bus progression) were addressed by five scenarios (Scenario 1: no bus priority, Scenario 2: signal preemption for buses, Scenario 3: Signal preemption for buses & exclusive bus lane, Scenario 4: Signal progression for buses, exclusive bus lane, Scenario 5: Signal progression for buses, signal preemption for buses, and exclusive bus lane). The use of exclusive bus lane was the most effective at reducing travel time, followed by preemption, then progression. Preemption was not as efficient as progression when considering schedule adherence. There was minimal impact to the traffic streams along the corridor and on the cross streets with the combination of an exclusive bus lane and progression providing the least disruption to normal flow. Another finding of the test was that the major factor affecting traffic flow in this corridor is signal system control parameters (isolated or coordinated timing plans, pre-timed or semi-actuated controllers). If only considering automobile delay, scenario 3 got the best result.

2.3.3 Field Tests in Portland, Oregon

An operational test at four intersections was conducted on Powell Boulevard, Portland in 1994[11]. Powell Boulevard is a five-lane arterial with three bus stations located at the far side and one is located at the near side. Green extension/early green and queue jump with shared right turn lanes were used at signals where far side a near side stations were located respectively. Extensions or early green time were allowed up to 10 seconds during off-peak periods and up to 20 seconds during peak periods. The queue jump with shared right turn lane was used in conjunction with a near side station to allow the bus to pull in front of the stopped queue. The performance measures included bus travel time, delay to not-transit vehicles, and person delay at the four intersections. Data collected showed about 6 minutes reduction in bus travel time during the peak hours due to bus priority. No significant impact on average vehicle delay or average person delay was found during peak hours. A little increase in average person delay during off-peak hours was noticed.

2.3.4 Field Tests in San Diego, CA

The use of passive priority to trolleys in downtown San Diego in addressed by Celniker in 1992 [12]. The high service frequency of trolleys (up to 27 per hour) brought lengthy delays for both private vehicles and trolleys themselves under the former signal preemption for trolleys. The active signal priority in favor of an area-wide timing plan designed to give signal progression to trolleys as they traveled between transit stops was abandoned. In the new timing plan, trolley drivers are instructed to wait until a fresh green appear after loading and unloading at a transit station. The trolley is ensured signal progression to next transit station as long as it departs within the first 3 seconds of the green time.

About 2 to 3 minutes travel time reduction through the 4.8 km corridor have been achieved through the use of passive signal priority. The drawback of the passive timing plan was also addressed: if a trolley failed to depart in the first 5 seconds of a green phase, it has to wait to the next green phase. Shortening the cycle length was considered to tackle this problem.

2.3.5 Simulations on Transit Signal Priority, Baltimore, MD

Signal progression to LRT vehicles was investigated in downtown Baltimore by Kuah in 1992 [13]. The corridor investigated in 2.4 km along Howard Street. The assumptions made include: 1) constant station dwell times of 30 seconds, 2) headways of 7.5 minutes in each direction along Howard Street, 3) cruise speeds of 40 to 48 km/hr along straight track sections, 24 to 32 km/h along curved track sections, 4) acceleration and deceleration rates of 0.84 and 0.76 m/s^2, respectively. Using the about assumptions time-space diagram for Central Light rail Line (CLRL) can be gotten.

A 30 second bandwidth was given to CLRL line based on travel time variability of the expected light rail train lengths and intersection crossing speeds. Simulation was made in TRANSYT under two scenarios: with and without CLRL for the year 1992.

Simulation results showed little or no degradations in level of service were encountered with the introduction of CLRL. However, the level of service declined from B to F at one intersection by simulation. Individual vehicle delay was predicted to increase 14% and the average operating speeds of vehicles in the study are predicted to decrease 7 percent with the introduction of CLRL.

2.3.6 Simulations of Transit Signal Priority, Seattle, Washington

A study of the signal priority to buses in Seattle area was reported by Jacobson in 1993 [14]. Two strategies were studied. The first is called HOV-weighted OPAC strategy. The people or vehicles through an intersection are maximized by using a dynamic programming algorithm. In this algorithm, the traditional signal timing constraints such as cycle length, signal split, and offset were ignored. The result showed this algorithm outperforms the conventional signal timing method.

The second strategy was called "lift" strategy. The presence of buses was identified by the upstream loop detectors. The signal is designed as if all traffic on approaches non-concurrent with the bus 's phase does not exist ("lifted") for a given amount of time. The control parameters of this algorithm were the location of bus detectors and the time during which traffic is "lifted". They can be adjusted according to intersection geometry, time of day, traffic volumes.

TRAF-Netsim was used to do the simulation. When "lifted" strategy was used to isolated intersection, 33% decrease in bus delay and minimal impacts to private vehicles were founded. When "lifted" strategy was simulated on 3 adjacent intersections, the benefits to buses were marginal and negative impacts to private vehicles increased.

The author noted that "lift" strategy does not work well with closely spaced intersections. Providing progression for buses and private vehicles was recommended by the author.

2.3.7 Simulations on Transit Signal Priority, Ann Arbor, Michigan

A 1995 report by Al-Sahili addressed the study of the effectiveness of transit signal priority strategies on Washtenaw Avenue in Ann Arbor, Michigan [15]. The arterial is 9.7 km long with 13 intersections. Bus headway along this arterial is 15 minutes during peak hours and 30 minutes during off-peak hours. Typically far-side bus stations and 2 phase timing plans were used in this arterial. The following cases were simulated in TRAF-Netsim with field collected traffic flow.

Base case: no preemption used. Traffic operates according to the optimal signal timing generated by TRANSYT-7F.

- Case 1: Green extension and red truncation without compensation to the cross street traffic after priority to buses.
- Case 2: Green extension and red truncation with compensation to the cross street traffic after priority to buses only if cycle failure is imminent.
- Case 3: Phase skipping without compensation: When green extension or red truncation are not sufficient to allow buses to pass intersection, the cross street green phase is completely skipped for one cycle without compensation.
- Case 4: Phase skipping with compensation: similar to Case 3 and compensation is provided as that in Case 2.
- Case 5: Selective plans: The most suitable form in the upper 4 cases is used at each intersection.
- Case 6: Case 5 is used only when a bus is behind schedule.

Other constraints included: 1) minimum green time for any phase is 10 seconds, 2) maximum green extension or red truncation is 10 seconds, 3) bus priority can not be used in 2 consecutive cycles.

Results showed that when arterial traffic is significant, compensation for the cross street traffic is not advisable. Results also showed along some sections of Wahstenam Avenue with heavy traffic, signal progression got better vehicle delay than signal priority.

Person delay was also used as a measure to compare the performance of each scheme. Average auto occupancy and average bus occupancy were set 1.3 and 25 respectively. The results showed Case 1 has the smallest average person delay and Case 4 has the largest. The effect of skipping phase skipping was observed using TRAF-Netsim' graphical animation. Under heavy traffic, both the bus and some other vehicles share the bus approach will pass the intersection when phase skipping priority is granted, thus longer queues will be formed at downstream intersection. This affect bus travel time negatively.

Overall, the most beneficial priority algorithm based on the simulation results is Case 5 (Selective signal priority at each individual intersection).

In addition, sensitivity tests on the effects of different traffic volumes, arterial to cross street volume ratios, traffic mixes (percentage of carpools), and random number seeds.

Five volumes were used in the simulation with only Case 5 by varying from 20% less than the original volume to 20% greater than the original using 10% increments. It was found that the additional delay (delay per vehicle) brought by Case 5 increase at higher volumes. That means signal progression is more important than signal priority at heavy traffic. The animation showed hat benefits brought by signal priority at one intersection were lost at the downstream intersection at high volumes, since the already saturated (or near saturated) conditions were worsened by the vehicles receiving signal priority at the upstream intersection.

Average person delay was the almost same with and without Case 5 with the exception that at the lowest volume average person delay was a little lower with Case 5.

The sensitivity of all the signal priority techniques to the ratio of arterial and cross street traffic volumes was also examined. An isolated intersection was used in the simulation. The ratios of arterial traffic to cross street traffic used were 2:1, 3:1, 5:1. And the volume of the arterial street ranged from 1000 to 2000 veh/hour, then use the ratio to calculate the cross street volumes. Results showed that the negative impacts brought by various signal techniques are significant at low volume ratios (2:1), but insignificant at high volume ratios (5:1). And the ratio 3:1 seems to be the cutoff value for if compensation should be use. At ratios above 3:1, compensation is not recommended. At volume ratios below 3:1, the use of signal priority was found to be doubtful. But if priority is used, compensation is recommended. Compensation is best suited for low volume conditions with low arterial to cross street volume ratios.

Results of the simulation also showed that the effectiveness of green extension and red truncation in terms of overall intersection delay was inconclusive. Delay was found to increase with phase skipping. But these strategies were effective under high arterial to cross street volume ratio conditions. Simulation also showed that random number "seed" didn't influence the network statistics significantly.

2.3.8 Simulations of Transit Signal Priority, Chicago, Illinois

In 1995 Bauer reported the simulation of providing priority to LRT vehicles in downtown Chicago (Chicago Central Area Circulator) [16]. The Central Are Circulator (CAC) is a LRT system Scheduled to begin operations in the year 2000. The CAC will have its exclusive lane.

TransSim II and TRAF-Netsim were used in the simulation. The simulated priority strategies includes: 1): fixed time controllers at intersections and semi-actuated controllers at junctions to give progression to LRT and automobiles. 2): In addition to strategy 1, green extension or red truncation should be used under request. 3): Delay of LRT is minimized through the use of interactive communication between LRT vehicles and the signal controllers, which allows LRT arrival times at intersections to be predicted.

The result showed that when strategy 3 is used, average speed of LRT is much higher that when strategy 1 or strategy 2 is used. Strategy 1 gets the minimal system-wide delay. Strategies 2 and 3 have the same amount of system-wide delay.

2.3.9 Bus Priority Control System in Maryland

The bus priority control system developed for the State Highway Administration provides both an advanced and extended green for rapid transit without disrupting coordination [17]. It is accomplished by using the multi-phase capability of the ASC/2-2100 controller to provide an advanced green phase that allows the rapid transit vehicle to "queue jump." In addition, the ASC/2-2100 coordinated phase split extension capability is used to extend the coordinated phase green time to insure passage of the transit vehicle through the intersection. Transit vehicles in the system are detected externally to the controller by using a priority control. The presence of a transit vehicle is signaled to the controller through a standard detector input. This is used to call the advanced green phase or to extend the coordinated green time depending on the state of the controller.

The first type of operation provided by the ASC/2-2100 Maryland Bus Priority Control System is an advanced green phase that allows the transit vehicle to enter the intersection prior to the start of green for the remaining traffic. This allows the transit vehicle to bypass queues of vehicles stopped at a signal (queue jump). If the transit vehicle approaches an intersection while the coordinated phases (normally phases 2 and 6) are red, an advanced green phase (phase 9 or 10) is selected to time prior to displaying green on the coordinated phase. The green output of the advanced phase is used to drive a special transit vehicle signal indication that is used to inform the driver of the transit vehicle of the queue jump period. Once the advance green period has timed, the controller advances to the coordinated phases, as there is no clearance period for the advanced phase.

The queue jump operation has no impact on coordination, as normal phases are used to provide the advanced green timing. If a transit vehicle is not detected while the coordinated phase is red, the advanced green time is added to the beginning of the coordinated phase green.

To insure that the transit vehicle is always given an opportunity to queue jump, the advance green phase is always selected to time prior to the coordinated phase if a transit vehicle is present. This means that if the phase preceding the coordinated phase has already began to terminate (advanced to yellow or red clearance) when the transit vehicle is detected, the controller will force the advance green phase as "Phase Next".

The second type of operation provided by the ASC/2-2100 Maryland Bus Priority Control System is the extension of the coordinated phase green for transit vehicles. If the coordinated phases are green when a transit vehicle is detected, the transit vehicle detector input is switched to the coordinated phase. This allows the transit vehicle to extend the green timing of the coordinated phase up to the maximum time allowed by the coordinated phase split extension period. If the transit vehicle is moving with a platoon of vehicles in the green band of the artery, little if any extension will occur. However, if the transit vehicle is lagging the green band, the split extension capability will allow the transit vehicle to hold the green until it has cleared the intersection.

2.3.10 Simulations of Transit Signal Priority, Austin, Texas

A 1997 report by Garrow addressed the simulation of transit signal priority on a 4.1 km long arterial with 11 intersections in Austin, Texas [18]. The data collected on signal timing, link lengths, traffic volume, turning percentage was input to TRAF-Netsim to create three models: 1) Peak period local bus, 2) off-peak period local bus, 3) off-peak period express bus. The local bus headway on schedule is 10 minutes during both off-peak and peak hours. Express bus model has less bus stations and longer headway than model 1 and model 2 (10 minutes for local bus during both peak and off-peak hours, and 30 minutes for express bus).

The following results were obtained:
1. Shortening cycle lengths may be useful during off-peak hours. If the cycle length is not reduced from its peak period length too much, reducing cycle length may benefit both transit as well as other vehicles along the arterial and cross streets by reducing delay.

Phase splitting maybe considered during off-peak hours. The overall effectiveness of phase splitting is somewhat uncertain.

Unconditional priority offers considerable potential for express transit during off-peak hours, especially when there are no limits on green extension or red truncation length. It is recommended to limit the length of green extension or red truncation length when at major cross streets. At minor cross streets, it is not so important to limit the length of green extension or red truncation.

During peak hours, the cross street saturation level and the amount of green time taken from the cross street are important factors in determining whether signal priority should be used at any intersection. Taking 5 and 10 seconds of green time from cross streets with saturation level over 0.9 and 0.8 respectively can cause signal plan failure.

Far-side bus stations are more favorable to transit signal priority than nearside bus stations.

Transit signal priority does not affect the overall average person travel time at intersections with significant cross street saturation levels.

Transit signal priority was determined to be ineffective within an arterial street environment. With the 10 minutes bus headway and the heavy traffic volumes used in the simulation, the negative impacts on cross streets by transit priority overwhelmed the benefit received by bus passengers. Only when shorter bus headways and high bus occupancies causes significant increases in transit's mode split does transit signal priority begin to become a viable option.

2.3.11 Field Tests of the OPTICOM System in the USA

OPTICOM is a priority control system used to give priority to both emergency and transit vehicles at signal-controlled intersections. OPTICOM based systems have been implemented at over 40,000 intersections world wide, including systems in Bremerton (Washington), Charlotte (North Carolina), and Orlando (Florida) [19]. The priority system has been used in different ways at different locations. In Charlotte OPTICOM has been used when providing priority to an express bus route since 1985. Priority is provided on intersection level along the length of an express bus route. Green extension and early green time are used to ensure priority. The green extensions and red light reductions typically add 10-15 seconds to the green phase and reduce the red phase by the same amount. OPTICOM has been combined with the Integrated Fleet Operations system in Orlando, Florida. It has been used to pinpoint the location of buses and determine if they are behind schedule. If they are running late the OPTICOM priority control system is activated and extensions or recalls provided as the bus moves through signalized intersections.

Benefits in Charlotte include a four minutes reduction in travel times and a more reliable and regular service. Ridership on the express bus route has doubled in the ten years since the service has been in operation. In Phoenix, Arizona the OPTICOM system saved transit buses an average of up to 15s per intersection. Improvements in timetable adherence and increased ridership were also reported. There was a small increase (1.4%) in delay to other traffic.

2.3.12 Field Tests in Brisbane, Australia

Brisbane City Council (Australia) developed an active bus priority system called the RAPID bus priority system, based around its own Urban Traffic and Control system known as BLISS (Brisbane Linked Intersection Signal System). The bus priority system was installed to provide priority at 14 sets of traffic signals in a trial of the system on Waterworks Road in Brisbane [20]. The literature indicates that the trial results were successful (No details available) and the system has been extended city-wide. In addition, the system has been installed in Auckland, New Zealand.

BLISS is a PC based UTC system. The road network is divided up into regions, each under the control of a single PC. Each PC can coordinate up to 63 sets of traffic signals and is located near the intersections to reduce communication costs. The whole system is supervised by a system master, which is also a PC, providing effective control over all the signals within a city. Brisbane currently has 650 signalized intersections under the control of a single system master PC and 11 regional master PCs. Each of the regional PCs communicates with local coordination modules via a modem and from there to the local intersection controllers. The local co-ordination modules talk to the intersection controllers using the SCATS protocol, as used by all intersection controllers manufactured for use in Australia, but other controllers with standard serial and parallel I/O interfaces could also be linked to BLISS. The local coordination modules are also used to drive Bus Information Signs at bus stops, which give predicted arrival times for the next four buses due at the stop.

In BLISS, signal timing plans are calculated off line, using TRANSYT, for different times of the day and for special shopping periods and special events. Current traffic parameters, such as volumes or occupancy are measured and recorded for all locations every five minutes and the appropriate plan selected according to predefined schedules. Operators can also use traffic surveillance cameras to monitor the network. In the event of unusual traffic conditions the operators can intervene and make changes to the signal timings. To assist them, BLISS continuously looks for abnormal congestion by comparing traffic volumes and occupancy levels against previously recorded average values for the particular time-of-day and day-of-the-week. A special mode is also used during periods of very light traffic.

When a bus is detected at advance loops or at the stop line loops of an intersection then, if required, priority is activated at the current intersection. Priority calls may also be made to nearby downstream intersections if there are no intervening bus stops. For best results it has been found that the advance loops should be beyond the longest queue and at least 90 meters back from the stop line.

After the bus is detected a check is performed by the regional master computer to see if it qualifies for priority. If it does, then the regional master sends priority messages to the appropriate local controller units.

Each time a bus is detected the information received is stored in a database. This information is then used to automatically build up a bus schedule that is then used to help determine whether future buses should get priority. The data in the database stores the service number, the bus start time and the day type. There are 12 different day types, namely; Mon-Fri school-in, Mon-Fri school-out, Saturdays, Sundays and Public Holidays.

When a bus is detected at a loop, RAPID determines whether it is late when compared with the average recent progress of buses of the same service number, start time and day type. In the original system a bus was qualified for priority if it was late by more than two minutes. In the system now being implemented a zero minute late threshold is to be used as experiments showed that providing priority to all transit vehicles does not impose a detrimental effect on other traffic.

The strategies used to ensure the bus gets a green signal at the junction include starting a phase early, extending a phase, not skipping a phase because a bus is known to be approaching.

If there is a priority conflict at an intersection, a decision has to be made about which vehicle gets priority. For buses, this is determined by a priority level based on the number of passengers on the bus and the level of lateness. Normally the bus with the most passenger boardings receives the priority.

The bus priority system uses an AVL system known as VID. The VID system locates any number of buses in real-time at consistent locations. A VID tag is fitted to the underside of each bus. When the bus drives over a loop in the road, a message transmitted by the tag is picked up by the loop and decoded by the VID receiver in the traffic signal controller cabinet. The message is then relayed to the BLISS system using the existing communications infrastructure. Each tag on the bus is interfaced to its electronic ticketing machine (ETM). The message transmitted by the tag consists of a static part and a dynamic part. The dynamic part is provided by the ETM and consists of the service number, the scheduled start time and the passenger loading. The static part identifies the bus owner and the bus number.

A field evaluation of the system concluded the following. Interventions that extended a phase on the main road reduced transit vehicle delay for vehicles receiving priority by 20 seconds on average. Similar interventions for cross-streets reduced transit vehicle delay by 90 seconds on average [21]. Interventions that start the phase early were found to produce reductions in transit vehicle delay in the range of 7 seconds. However, the study failed to produce statistically significant savings in travel times over the entire 7-km test section.

2.3.13 Field Tests in Lyon & Toulouse, France

The CELTIC bus priority method was developed as part of the experiments in Lyon against a background of fixed time UTC. A conditional priority strategy was developed incorporating state estimation and optimization at each intersection over a 50-second horizon [22]. For private vehicles an estimation is required from loop sensors of the number of vehicles queuing while for each bus an estimate is made of the time to reach the stop line at free-speed and the time to clear the queue in front of the bus. Various criteria are used for conditional priority including the minimization of delay to public vehicles while minimizing the difference this causes between the resulting phase change times and those of the background plan sequence.

Field tests of the system in Toulouse indicated that statistically significant reductions in transit vehicle travel times in the range of 11 to 14 percent were obtained, however, no statistically significant changes in the general traffic travel times were observed.

2.3.14 Field Tests in Strasbourg, France

A transit priority system developed by CGA (An industry in France) that used in Strasbourg, France and a few other French cities was tested in the field [23]. The system uses a beacon-based approach where the UTC system communicates with the transit vehicles prior to any phase change to determine whether a green extension or early actuation is required. The study concluded that system-wide reductions in travel times in the range of 4 to 5 percent were achievable if the frequency of buses was low (in the range of a transit vehicle arrival every one, two or three signal cycles).

2.3.15 BALANCE in Munich, Germany

BALANCE is a traffic signal control method developed in Munich [24]. Realization of priority for transit vehicles at the operational level is through priority preemption (phase change), green time extension and special phases. A predetermined priority level ranges from absolute priority (no delay, if there are no competing public transport vehicles) to no priority. At the tactical level, one of four priority levels is selected depending on the general traffic situation, and particularly the delay suffered by competing transit lines. BALANCE incorporates an objective function for optimization based on a performance index, PI, which is composed of a linear combination of the criteria "delay suffered by persons using private traffic" and "delay suffered by persons using public transport vehicles". Optimization can therefore be performed according to weight in the range 0-1 related to the influence given to each criterion. Evaluation of BALANCE was undertaken in LLAMD at one intersection using microscopic simulation incorporating the actual detection and control methods existing on street. Field trials were also carried out in Munich on a network where 21 intersections were equipped to provide priority. Travel time savings for transit s of 14% were recorded. Delays to both cars and trams were reduced following the introduction of BALANCE.

2.3.16 Transit Signal Priority in Stuttgart, Germany

In Stuttgart, three levels of transit signal priority have been developed to encourage the use of light rail system. Three levels of priority can be granted [25]. The first level, called "limited preferential treatment" allows green extensions when required. The second level allows both extensions and recalls, but there is a limit to the maximum red time allowed for opposing phases. The third level gives absolute priority without any red time constraints being imposed. Delays to transit vehicles have been reduced by 50%, with little extra delay to private vehicles, by using the limited preferential treatment priority level.

2.3.17 Transit Signal Priority in Zurich, Switzerland

Zurich has a highly successful integrated transport system that enjoys high levels of patronage [26]. A priority system for public transport vehicles has been developed with the aim of reducing their delay to zero. High annual trip rates of 490 per person are also reported. This compares with 131 for Manchester, 250 for Stuttgart and 290 for London. Swiss politicians regularly use the public transport system in Zurich, not just at election times. On detection of a public transport vehicle the local controllers ensure that the vehicle will receive a green light at the upcoming intersection. The detection information is also passed to adjacent intersections so that local optimization can be performed and to a central computer where more strategic decisions are made, based on optimization of the whole network. Metering is also used to keep public transport routes free of congestion. It is claimed that zero waiting time for public transport is achieved at about 90% of signalized intersections.

2.3.18 Field Tests on Queen Street, Toronto, Canada

The field study of non-optimizing signal priority strategy for streetcars along a 1.6 km section of Queen St., Toronto was reported in 1991[27]. Queen St. consists of 4 lanes with two-way streetcar service (6near-side stops, 1 far-side stop, six signalized intersections and no exclusive streetcar lanes). Headway of streetcars is about 4 minutes during peak hours and 5 to 6 minutes during off peak hours. Green extension and red truncation were used for granting signal priority. The upper bound for green extension is 14 seconds. In order to use the green time effectively, the status of the streetcar (still in need of priority or downstream from the intersection). If a streetcar arrives at an intersection during its red phase or in the latter part of its green phase, a fixed 6 seconds red truncation was used to ensure pedestrian safety. The original timing plan for this section is coordinated for traffic progression. When signal priority is given, the original timing plan is released. When the priority is finished, the original timing plan is restored. A few of the subsequent cycles will be shorted to resume the coordination with other intersections.

From the data collected streetcar delays and travel times decreased with the introduction of priority. This resulted in a large reduction in average passenger delay due to the high transit occupancy. Negative impacts to the cross street were minimal. But the signal priority awarded to Queen St. disrupted the signal coordination between the Queen/Bathurst intersection and Richmond /Bathurst intersection. Spillback was noticed. Investigation of simultaneous priority of the two intersections was recommended. Another finding is that green extension were far more effective that red truncation (only 12% of the red truncations were fully used by a streetcar).

2.3.19 Field Tests on Queen and Bathurst Street, Toronto, Canada

A report on SPPORT is presented by Yagar in 1992 [28]. SPPORT attempts to minimize the over cost (or delay) to all bus and private vehicle passengers at an intersection. Detectors were located 150 and 1000 meters upstream from an intersection. These detectors can differentiate streetcars from private vehicles. Current queue lengths and future arrivals can also be obtained from these detectors. Given the information, SPPORT generates a five-second long plan to minimize total intersection delay. This plan is reevaluated after a five-second duration and a new plan is implemented. This process is repeated continuously. The new plan is selected from a list of possible new plans. Priority for transit vehicles can be implemented by giving high priority to timing plans conducive to transit operations.

The Queen and Bathurst Street intersection in Toronto was simulated to test the effectiveness of SPPORT, where streetcars are operated alongside normal traffic. Three sets of timing plans were used: 1) fixed timing plan, 2) SPPORT generated timing plan (no priority given to streetcars), and 3) SPPORT generated timing plan (priority given to streetcars).

The results of the simulation indicate a near 50 percent decrease in both average person delay and average vehicle delay. It was said by the author SPPORT deals with the stochastic nature of loading and unloading time effectively, and the ability to deal with intersections within a network is planned for the future.

2.3.20 Field Tests on Uxbridge Road, London, England

The Selective Priority Network Technique (SPRINT) gives priority to buses at signals controlled by a fixed time UTC system. It has been developed and tested in a trial on the Uxbridge Road in London in 1996 [29].

When a bus is detected an algorithm is used to determine new signal timings which will let the bus through the next intersection at the earliest possible time. This algorithm uses a traffic model for both the bus and the other traffic and it attempts to optimize the signal timings subject to a number of constraints. It uses green extensions and early green to achieve its aims. Various constraints are also used to ensure that the disbenefits to other traffic are not too great. For each intersection the traffic engineer can decide

- Whether both extensions and recalls are allowed or just extensions
- The maximum number of cycles that SPRINT can run timings different from the base plan
- The maximum time difference of a stage from the base plan
- The maximum levels of saturation allowed for each of extensions, recalls and recovery periods
- No two recalls can happen consecutively.

Subject to these constraints SPRINT can make one of five decisions when a bus is detected:

- No operation - No action can be made which would give priority and satisfy the constraints.
- Central extension - An extension is requested by the central UTC computer.
- Local extension - An extension is provided to the bus by the controller on street, this is sometimes required, rather than
- Using a central extension, to overcome transmission delays.
- Stay - No action is required to ensure the bus gets a green at the next junction, but make sure that any following buses do
- Do not change the signal timings to change this situation.
- Recall - Call a later stage to give the bus priority.

A trial of the SPRINT system has been carried out on eight junctions of the Uxbridge Road in London [30]. The trial section covered 3km and includes 11 bus stops. There were up to 40 buses an hour in each direction. The main benefits obtained were an average of 2.0 seconds reduction in delay per junction for buses on the main road links and 6.4 seconds reduction for buses on side road links. During the trial the proportion of actions requested by SPRINT were as follows: Green extensions (5%), Green recalls (25%), No priority required (67%), No priority available due to constraints (3%).

2.3.21 Transit Signal Priority in Swansea, England

Evan reported the transit priority in Swansea, England in a 1994 report [31]. Exclusive bus lane with both passive and active bus priority were introduced in Swansea. Passive priority is granted by biasing the bus approaches using SCOOT. The active priority strategies include green extension, red truncation, and insertion of a green bus phase.

From field-testing, exclusive bus lane reduced the total person-delay significantly. With passive priority, bus delays decreased by 2%, while delays to other approaches user increased by about 17%. When green extension or red truncation were used, delays to bus passengers decreased by about 11% during peak hours and delay to private vehicles increased by about 7% during the evening peak hour and no increase during morning hour was noted. With the use of green insertion, no decrease was noticed and the increase in delays to private vehicles was about 15%.

2.3.22 Simulations and Field Tests in London, England

Hounsell address the simulation and field testing in London in a 1996 report [32]. Active bus priority is operated within SCOOT. Buses are typically detected 70 to 100 meters upstream a intersection. Priority is granted through green extension or red truncation only when the saturation level of non-priority approach does not overpass the pre-set limits. SCOOT Testing and Evaluation Program (STEP) was for simulation. The results gotten from simulation include: 1) Bus delay savings increase as the saturation level of the intersection decreases. 2) Cutoff value of saturation level beyond which priority should not be used are 110% and 90% for green extension and red truncation respectively. 3) Usually green extension is more effective than red truncation because the former is less disruptive. 4) The distance of inductive loops upstream from the intersection should be far enough while accurate prediction of bus arrival time should be granted. In the field-testing, data collected included bus travel time, traffic flow at intersections, intersection delay and congestion, signal timing, degree of saturation. Four priority methods were compared: 1) green extension under central computer control, 2) green extension and red truncation under central control, 3) green extension under local control, 4) Green extension and red truncation under local control. The results showed the third priority method (green extension under local control) is the best in terms of both bus delay and auto delay.

2.3.23 UTOPIA in a few European cities

Transit signal priority is several European cities was reported by Nelson in 1993 [33]. UTOPIA traffic control system has been used to collect the real-time information of position, occupancies, and potential defects of public transit vehicles in Turin, Italy. Priority to public vehicles was given by weighting transit approaches more heavily when determining signal splits. UTOPIA is a network level system. It divided the network into overlapped zones. Every strategy was implemented for 3 seconds, and then new strategy would be generated based on the real-time information. In the trial, 19% increase in average vehicle speed was perceived. In Wil, Priority to transit was granted by advanced information technologies. Information of schedule adherence, transit vehicle destination, and transit vehicle occupancies was maintained and communicated to a central controller by the on-vehicle computer. Presence of transit vehicles near intersections was communicated by infrared information system.

2.4 Conclusions

Numerous transit signal priority systems have been developed and implemented in around the world. These systems appear to offer significant potential benefits to transit vehicles, without seriously compromising competing traffic. These have been used to give priority for buses, trams/light rail, and even emergency vehicles. Most of the priority schemes are based on a handful of possible interventions, including: green extension, early green, introduction of a special phases, phase suppression, and green truncation.

Several factors can impact the success of a transit signal priority system. The main factors include:

- Frequency of transit vehicle arrivals,
- Transit vehicle occupancies,
- Level of congestion at the signalized approaches,
- Capacity of the transportation network, and
- Intelligent Transportation System technologies available to signal priority.

The literature indicates that transit signal priority has the potential to enhance transit vehicle operations in terms of improved schedule reliability, reduce operating costs, and attract ridership. However, it is not clear how sensitive the results are to different traffic and transit related factors. In addition, it is not clear under which traffic conditions system-wide benefits are attainable. Consequently, the following chapters will attempt to answer some of these issues.

3 MODELING TRANSIT SIGNAL PRIORITY ON COLUMBIA PIKE

Currently, the Washington D.C. Region Intelligent Transportation System (ITS) Task Force is considering implementing signal preemption and other alternative vehicle priority strategies along signalized arterials in the Washington D.C. metropolitan area. As part of this effort, a simulation study is conducted to evaluate the potential benefits of implementing transit priority along major arterials in the region. Two other important goals of this study were to evaluate the potential benefits of using adaptive signal control systems to control traffic along busy arterials and to determine the potential benefits of integrating transit signal priority with adaptive signal control.

This chapter documents the main modeling tasks of the simulation study that was conducted. This chapter describes the test corridor that was chosen for the simulation study, the study approach, the data collection efforts that were conducted to generate a simulation model of the test corridor, and the various signal control strategies that were considered.

To conduct the simulation study, a 21-intersection section of the Columbia Pike arterial in Northern Virginia was selected as a test corridor. This section, which extends from the Pentagon building to the east up to Carlin Spring Avenue to the west, was based on two main factors, namely, the highly traveled traffic volume (approximately 26,000 vehicles per day) and high transit ridership (highest in the Northern Virginia region) with over 9,000 daily passenger trips. Another important consideration was the recent installation of a SCOOT adaptive traffic signal control system along the corridor, which added a unique opportunity to evaluate the combined use of transit priority and adaptive signal control.

The study uses the INTEGRATION microscopic traffic simulation model to perform the evaluations. To fully evaluate the potential benefits transit priority along the selected test corridor, five priority and six signal control scenarios are considered for both the AM Peak and Midday travel periods. The priority scenarios consider providing no priority at all, priority only to express buses along Columbia Pike, priority only to regular buses along Columbia Pike, priority to both express and regular buses along Columbia Pike, priority to buses on streets crossing Columbia Pike, and priority to all buses. On the other hand, the signal control scenarios allow a fixed-time signal operation to be simulated, as well as observed SCOOT timings and four alternative timing strategies in which the green split, offset and/or cycle time are determined by the INTEGRATION signal optimization routines every 5 minutes based on observed traffic conditions.

3.1 Study Corridor

To evaluate the potential benefits of implementing transit signal priority in the Washington D.C. region, a 21-intersection section of the Columbia Pike arterial in Northern Virginia was selected as a test corridor. The location of this arterial within the Washington D.C. region is illustrated in Figure 3.1. This section of the Columbia Pike arterial was selected for a number of reasons. First, it is a busy arterial that is traveled by approximately 26,000 vehicles per day. Second, the arterial serves several federal agencies employing over 40,000 people, including the Pentagon and the Navy Annex at the corridor's eastern end, in addition to linking medium-density residential neighborhoods with retail businesses. Third, the arterial shows the highest transit ridership in the Northern Virginia region with over 9,000 daily passenger trips (Arlington Department of Economic Development, 2000). Finally, the recent installation of a Split Cycle and Offset Optimization Tool (SCOOT) adaptive traffic signal control system at a number of intersections along the corridor added the unique opportunity to evaluate the combined use of transit priority and adaptive signal control.

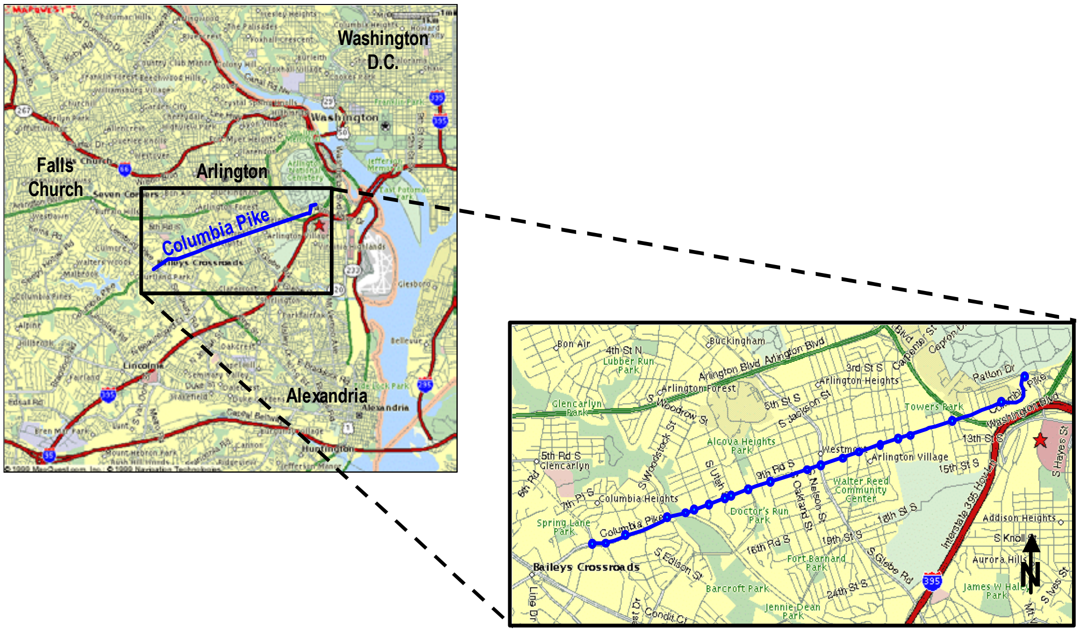

Figure 3.1: Columbia Pike Study Area

The remaining portions of this section provide a more detailed characterization of the test corridor. The first sub-section describes the main geometrical elements of the corridor, while the three remaining sections successively describe the corridor's traffic signal control system, general traffic conditions, and current transit operations.

3.1.1 Corridor Geometry

The geometric layout of the section of Columbia Pike that was selected as an evaluation corridor is illustrated in Figure 3.2. As shown in the figure, the section extends from Carlin Springs Avenue, at the corridor's western end, to Joyce Avenue, near the Pentagon Building at the corridor's eastern end. This section further extends over a total distance of 6.354 km (3.95 mi) and crosses a number of major cross-street arterials, such as Carlin Spring, George Mason, Glebe, Walter Reed, Washington Boulevard, and Joyce.

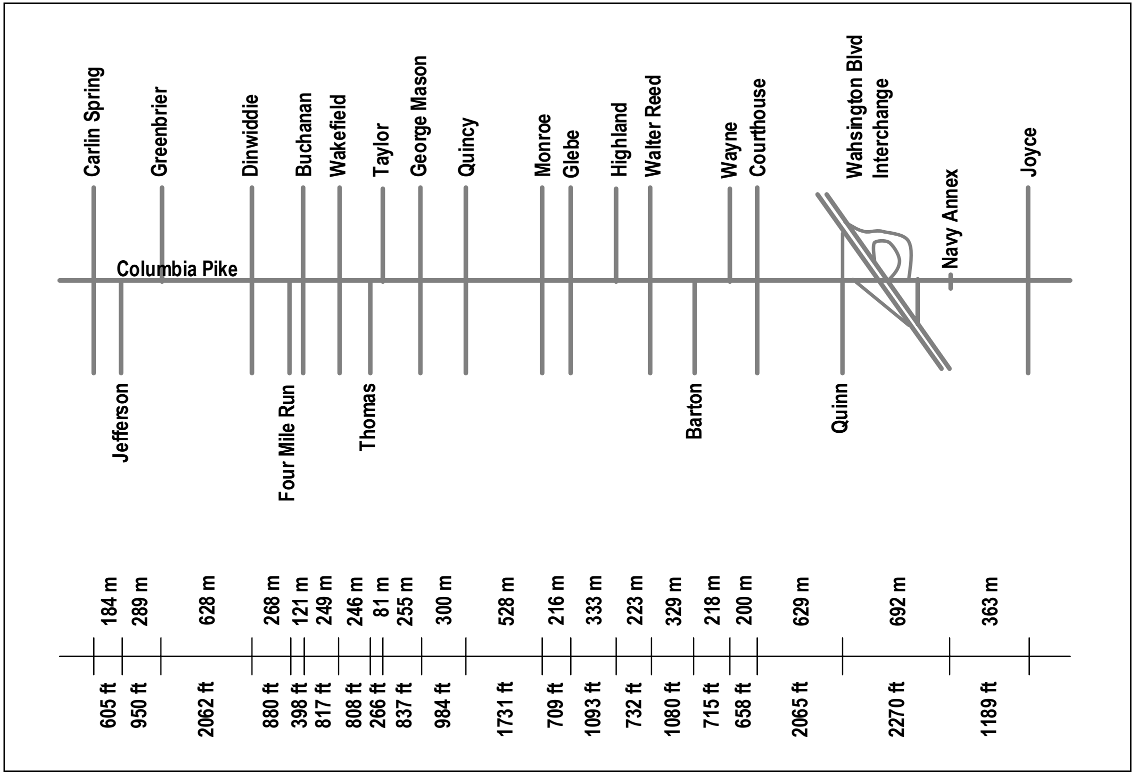

Figure 3.2: Study Corridor Layout

From a geometry point of view, the corridor features a relatively straight horizontal alignment. As it is seen in Figure 3.1, there is only one major curve near the eastern end of the corridor, just before reaching the intersection with Joyce. Within the alignment, the signalized intersections are also relatively well spread. The shortest distance between two successive intersections is between the intersections with Thomas and Taylor, where the stop line to stop line distance is 81 m (266 ft). Alternatively, the longest distance between two intersections is between the intersections with Quinn and Joyce, if the pedestrian signal at the Navy Annex. In this case, the stop line to stop line distance between the intersections with Quinn and the Navy Annex signal is 692 m (2270 ft), while the distance between the Navy Annex signal and the intersection with Joyce is 363 m (1189 ft), yielding a total distance of 1055 m (3459 ft) between the intersections with Quinn and Joyce. For the remainder of the corridor, the distances between adjacent intersections vary from 121 m (398 ft) to 628 m (2062 ft).

The vertical alignment of the study corridor further presents a number of uphill and downhill grades, as illustrated in Figure3.3. This profile was generated using GPS altitude data that were collected by probe vehicles that were driven along the study corridor. To generate the profile, a total of 13 eastbound and westbound runs were conducted. Based on the collected GPS data, the altitude of the eastbound and westbound stop lines of each intersection was first determined by averaging across the 13 observations. Following this calculation, the altitude of each intersection was then computed as the mean of the eastbound and westbound stop line altitudes. Finally, a vertical profile for the entire corridor was determined by linking the individual intersection elevations. Only one exception was made to this calculation to allow the resulting profile to account for the significant change in grade between the intersections with Greenbrier and Dinwiddie. As Figure 3.3 clearly demonstrates, a fairly good match thus exists between the resulting profile and the altitudes that were measured in the individual GPS runs. Similar matches were also found for other sets of GPS data collected along the corridor.

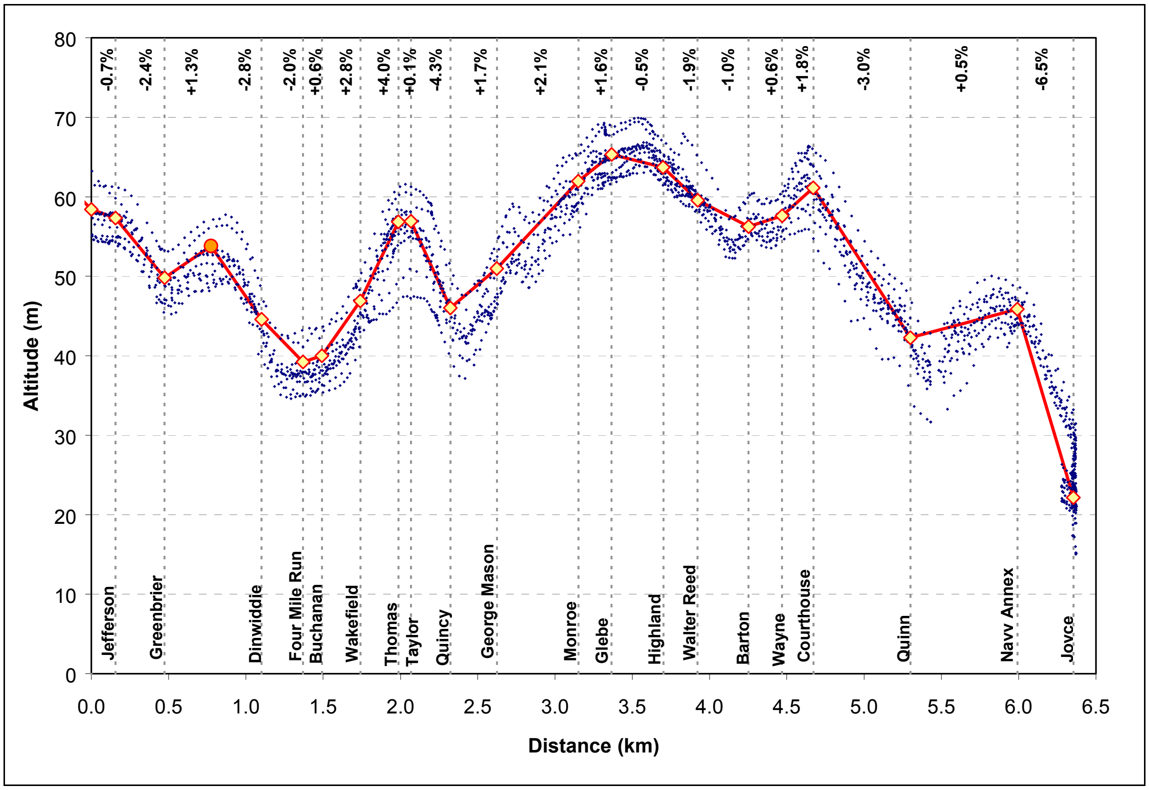

Figure 3.3: Study Corridor Vertical Profile

The illustrated profile and the grades listed in the upper portion of Figure 3.3 generally indicate that there are non-negligible changes in altitude along the corridor. While the intersection with Carlin Springs is located at an elevation of about 58 m (190 ft), the arterial's elevation drops to 39 m (128 ft) near Buchanan, before sharply going up to 57 m (187 ft) near Thomas and Taylor Streets, dropping again to 46 m (151 ft) near George Mason, going up once more to 65 m (213 ft) near Glebe and finally gradually dropping to 22 m (72 ft) at the intersections with Joyce. As a result of these altitude changes, grades exceeding 4% and up to 6.5% are observed on some sections of the corridor. The main impact of these grades on traffic flow performance is to cause slower accelerations and potentially slower speeds for vehicles going uphill, especially buses, as well as sharper accelerations and potentially higher speeds for vehicles going downhill. While this impact may not seems important, it may have a certain impact on the effectiveness of the priority strategy considered if transit vehicles have difficulties accelerating on the uphill sections of the corridor.

An additional important observation that can be made from the data of Figure 3.3 is the variability of GPS readings. This variability is attributed to GPS measurement errors. The majority of these errors are linked to the way distance is measured between a satellite and a GPS receiver. Since distance is measured by the time it a GPS signal takes l to go from a satellite to a receiver, any delay in the signal transmission thus results in distance overestimation and in inaccuracies in the estimated position of objects. Such delay can be caused by signals bouncing off mountains, bridges or buildings. Errors can also be caused by charged particles and water vapor in the upper atmosphere, which may slow down the signal transmitted by satellites. Additional measurement errors can finally be attributed to potential errors in the transmitted location of a satellite and errors within a receiver caused by thermal noise, software accuracy and inter-channel biases.

3.1.2 Traffic Signal Operations

As indicated in the Section's introduction, traffic movements along Columbia Pike are controlled by a SCOOT traffic signal control system. This system, which was installed in 1999 by the Arlington County, controls all the intersections along the corridor, with the exception of Carlin Spring, Jefferson, Greenbrier, Navy Annex and Joyce, which remain operated in fixed-time by an EAGLE MONARC system.

For the intersections controlled in fixed-time, different cycle lengths are used throughout the day to account for changes in traffic demand. Specifically, for the AM peak period, all the fixed-time intersections are operated with a 100-second cycle, with the exception of Carlin Spring, which is operated with a 130-second cycle. For the Midday period, the cycle length is fixed at 75 seconds at all intersections. For the PM peak period, both Carling Spring and Jefferson operate with a 140-second cycle, while Greenbrier, Navy Annex and Joyce are operated with a 105-second cycle. These changes in traffic signal cycle length are important for this study as they have a great impact on traffic flow patterns within the study corridor. Since traffic signals at both ends of the study corridor are controlled in fixed-time, any change in the duration of the signal cycle at these intersections affect the frequency at which platoons of vehicles are released towards the central section of the corridor and thus, the natural cycle length requirement for all SCOOT-controlled intersections.

Within the corridor, the SCOOT-controlled intersections have the capability to continuously adjusting their timings to observed traffic conditions. As an example, Figure 3.4 illustrates the signal timings that were implemented by the SCOOT system on June 5, 2000 at the intersection with George Mason. The figure clearly shows the adjustments made by the system, first to accommodate the increase in traffic demand between 3:45 and 7:30 PM, and then to accommodate smaller cycle-to-cycle changes. Of particular interest is the sudden increase in cycle length around 8:00 PM, probably to accommodate a sudden increase in evening traffic demand. It can also be observed that the cycle lengths implemented by SCOOT during the PM peak period had a duration that varied mostly between 100 and 106 seconds. This closely matched the fixed-time plan cycle length that was used at the intersections located at the eastern end of the study corridor, which featured a 100-second cycle length. It should be noted that the eastern end of the network generates a significant portion of the traffic traveling along Columbia Pike during the PM peak. Finally, the figure also indicates the ability of the system to skip the advanced green on the eastbound Columbia Pike approach when such a phase is not required, as well as its subsequent ability to redistribute the unused green between the two remaining phases to minimize changes in the cycle length.

3.1.3 Traffic Conditions

Figure 3.5 illustrates traffic flow data that were collected by the SCOOT system on the approaches to the intersection with George Mason between Monday, June 12, and Wednesday, June 14, 2000. For this intersection, the four diagrams shown in the figure indicate the existence of highly directional weekday flow patterns. The two upper diagrams first indicate that the peak period of travel in the eastbound direction along Columbia Pike occurs between 6:30 and 9:00 AM, while the peak period in the westbound direction occurs between 4:00 and 6:00 PM. Consequently, it can be determined that the majority of vehicles traveling along Columbia Pike move towards downtown Washington in the morning, and in the opposite direction in the afternoon. For the Midday period (11:00 AM to 1:00 PM), a more balanced demand is observed along Columbia Pike. For this period, flow rates varying between 600 and 800 veh/h are observed for the eastbound direction, while rates varying between 700 and 900 veh/h are observed for the westbound direction. Finally, as was the case with Columbia Pike, the two lower diagrams of Figure 3.5 also indicate directional flow patterns along George Mason. In this case, the majority of the traffic on the cross-street arterial is observed to move northbound in the morning, southbound in the afternoon, and again, with no clear directional pattern in the middle of the day. Finally, while the diagrams of Figure 3.5 illustrate traffic patterns at a single intersection, similar traffic patterns were also observed for all intersections for which SCOOT detector data were available, thus indicating that the traffic along the corridor generally moves eastward and northward in the morning, westward and southward in the afternoon, and with no clear direction in the Midday period.

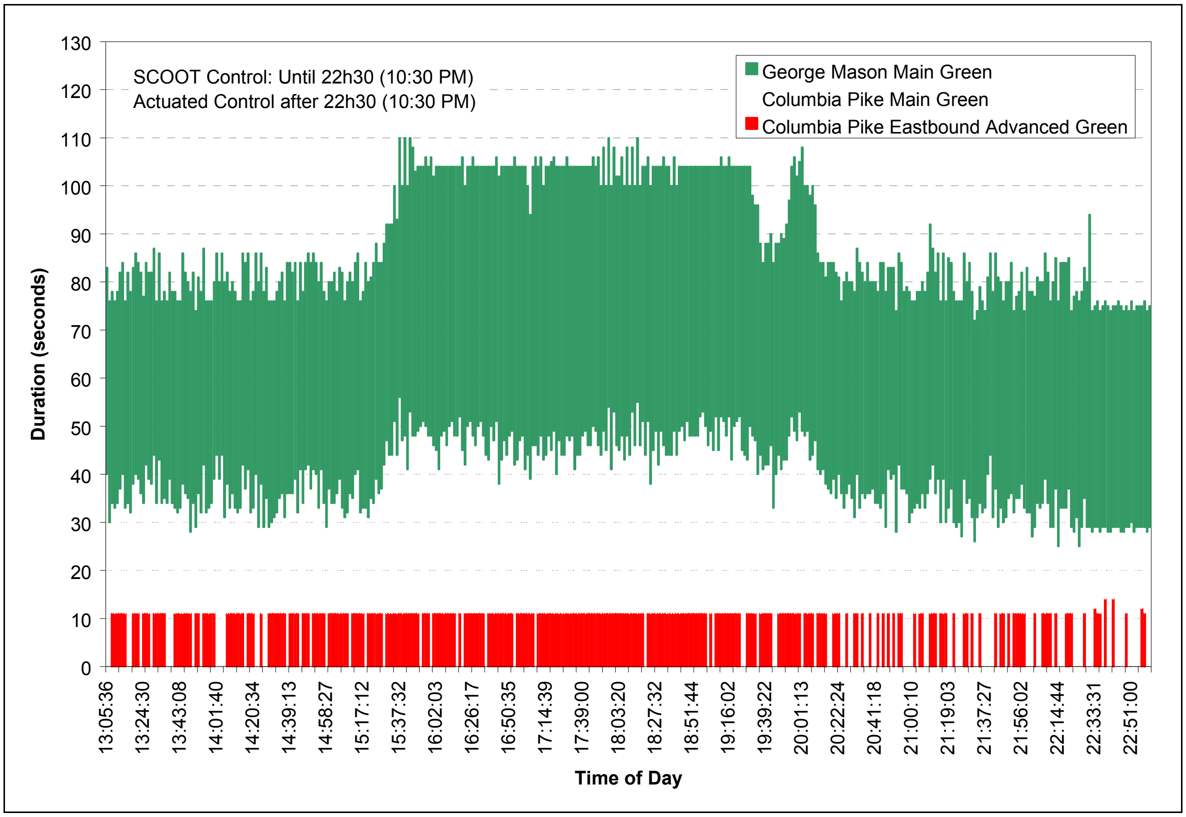

Figure 3.4: SCOOT Traffic Signal Timings at George Mason on June 5, 2000

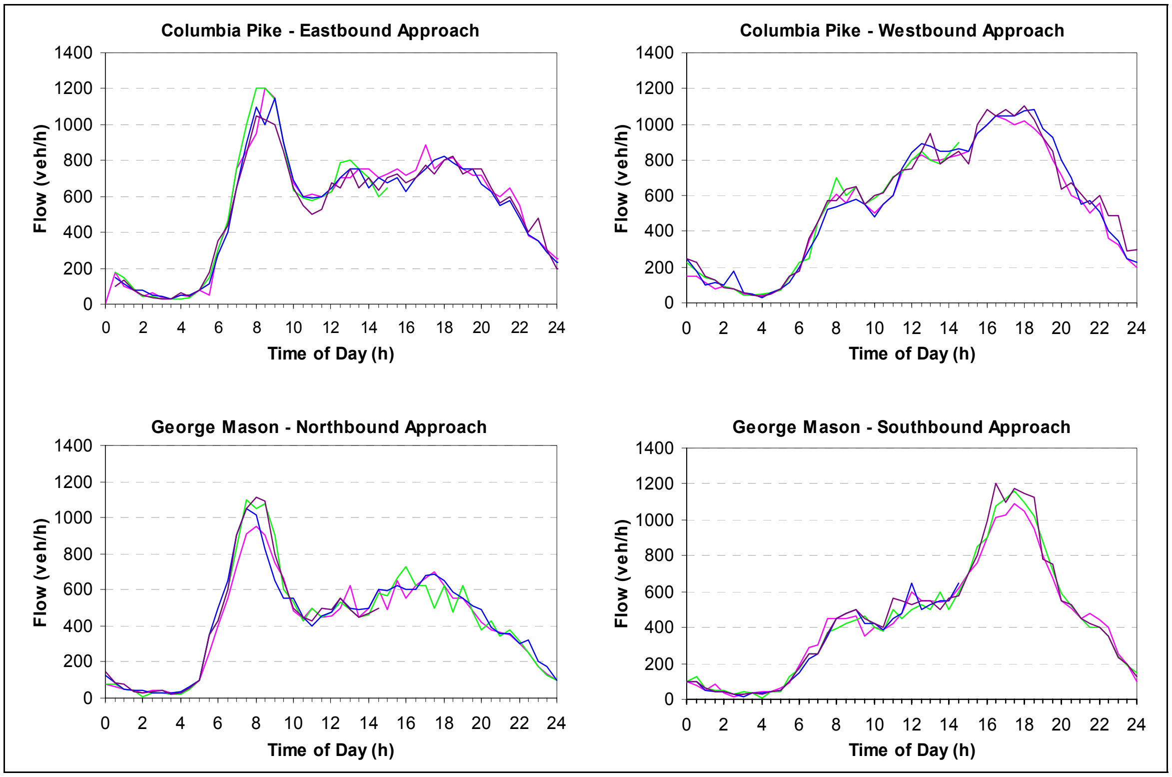

Figure 3.5: SCOOT Traffic Counts at Two Intersections

In addition to indicating the main directions of travel, the diagrams of Figure 3.5 illustrate the extent to which traffic flow varies from one day to another. For instance, during the AM peak period, the measured eastbound flows at the intersection with George Mason varied between 1000 and 1200 veh/h over the three-day period covered by the data. This represents a day-to-day variation of about 20%. For the rest of the day, differences in flow rates of 100 vehicles per hour are commonly observed. For a 500-veh/h flow rate, this results again in a variation of about 20%, which is far from being negligible. Figure 3.5 also illustrates similar variations in traffic flows throughout the day on the westbound, northbound and southbound approaches to the intersection. In addition, similar variations were also observed at all other intersections for which SCOOT data were available.

3.1.4 Transit Operations

Transit operations along Columbia Pike were characterized from field surveys and timetables published by the Washington Metropolitan Area Transit Authority. This section summarizes some of the data that were collected to determine transit service points along the corridor, characterize dwell times, evaluate bus occupancies and determine the degree to which transit vehicles adhere to the published schedules.

Figure 3.6 illustrates the location of the bus stops within the study corridor, while Figure 3.7 identifies the various bus routes servicing the illustrated bus stops during the AM peak, Midday, and PM peak travel periods. For the bus stops located along Columbia Pike, Figure 3.6 distinguishes between curbside stops, stops with bus bays, and stops requiring the buses to use exclusive right-turn lanes. This categorization is important for the evaluation of alternative priority strategies for transit vehicles in that it classifies the bus stops according to the degree of interference that dwelling buses may cause to the general traffic. The figure also allows bus stops to be categorized according to their position relative to the downstream intersection. As can be observed, the Columbia Pike corridor features nearside, mid-block and far-side stops. This variety of bus stop locations has a profound impact on the type of transit priority that can be implemented at each intersection, as nearside stops will not necessarily require the same type of changes in traffic signal timings to accommodate an approaching transit vehicle than far-side stops. Finally, both Figure 3.6 and Figure 3.7 indicate a number of intersections where buses traveling on conflicting approaches could issue conflicting priority requests if the operating policy is to attempt to accommodate all approaching buses. Of particular interest in this case are the intersections with Buchanan, Wakefield, George Mason and Walter Reed.

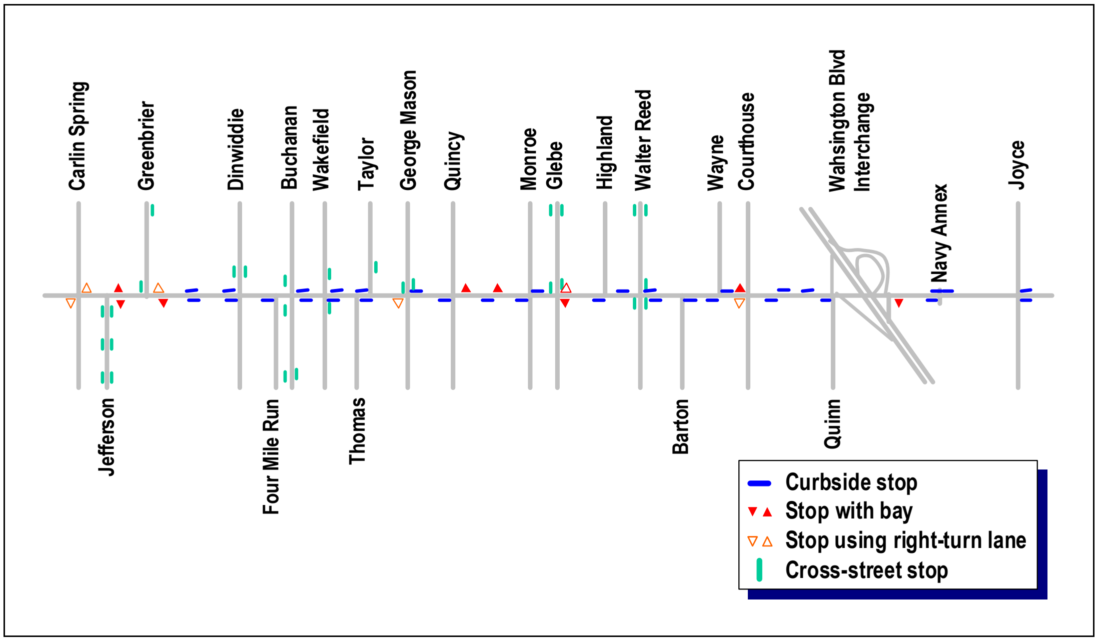

Figure 3.6: Bus Stop Locations and Types

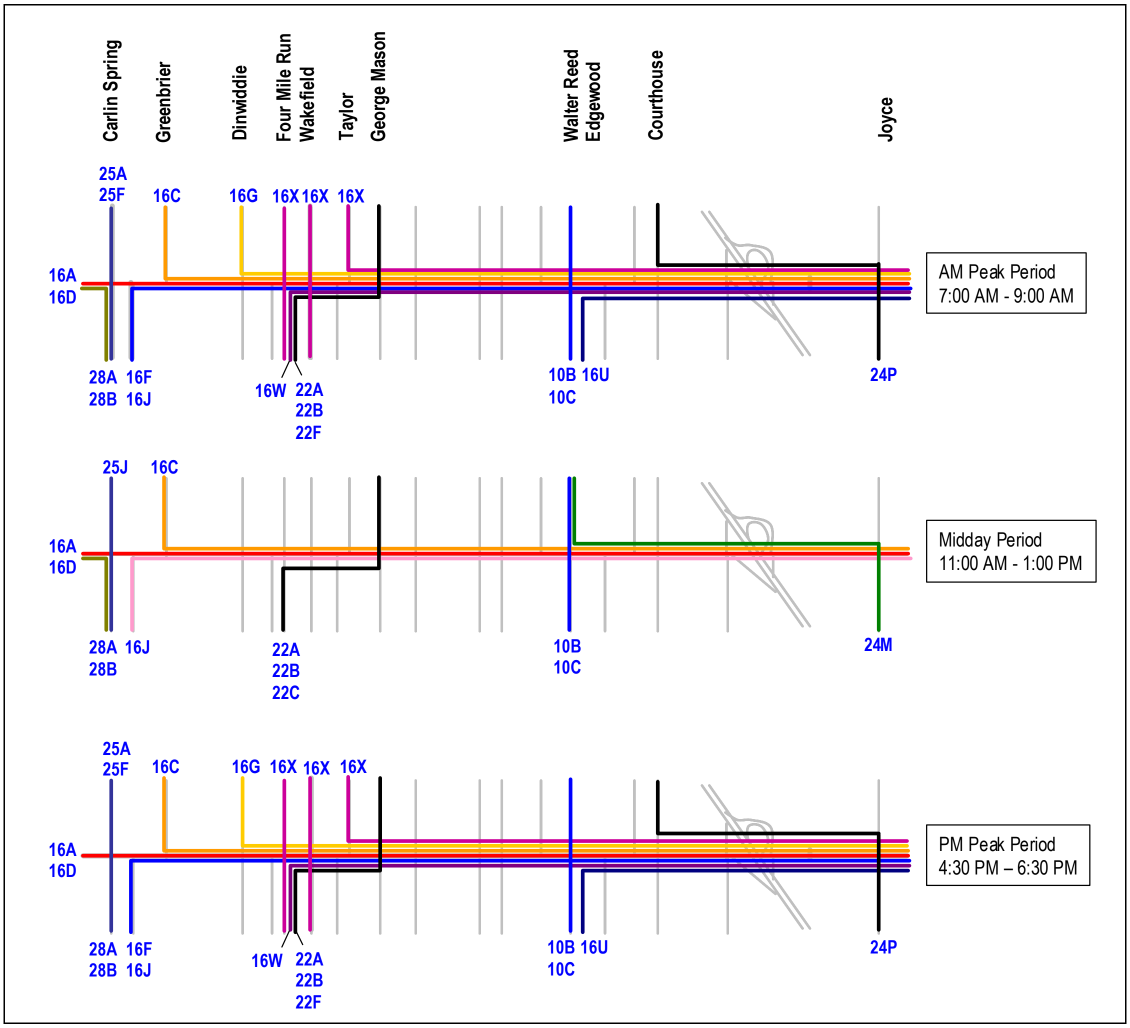

Figure 3.7: Transit Routes Traversing Study Corridor

Figure 3.8 further illustrates a series of dwell times that were observed along Columbia Pike at the bus stop located just downstream of the intersection with Walter Reed and serving riders traveling in the eastbound direction. While the figure shows a relatively high variability in dwell times, it also indicates that there are a significant number of buses that do not always stop to load and unload passengers. Specifically, over the 34 observations that were made, only 21 buses stopped. This is an important observation, as non-stopping buses will then reach the following intersection much sooner than expected when compared to buses that dwell at the bus stops.

In Figure 3.8 while an average dwell time of 19.2 seconds is calculated when considering only the stopping buses, the actual observed dwell times range from 4 to 50 seconds. The existence of such a range for a single bus stop points out the difficulty of predicting the exact moment at which transit vehicles are expected to reach an intersection, and thus, the difficulty in determining the moment at which these vehicles may require preferential treatment for crossing the intersection. This observation is emphasized by the data of Table 3.1, which provides a sample of observed dwell times at a number of stops along the corridor. Similar to Figure 3.8, it is observed from this dataset that there is significant variability in dwell times at almost every bus stop along the corridor, in addition to a significant number of buses that do not stop at all bus stops along their routes, thus creating large uncertainty in predicting bus arrival times over a series of intersections.

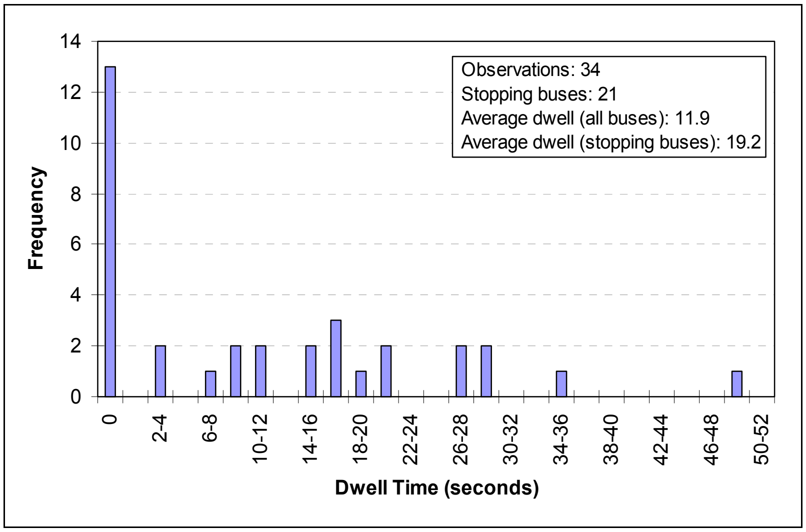

Figure 3.8: Observed Bus Dwell Times at Walter Reed (Eastbound)

Table 3.2 further provides a sample of bus occupancy data that were gathered on June 6, 2000. The table indicates bus occupancies for various routes that were surveyed during the Midday and PM peak periods. The figure demonstrates that the bus occupancy varies significantly within the collected sample. On the one hand, the highest recorded occupancy is 63 passengers on a bus leaving the Pentagon Building, just outside the corridor's eastern boundary, at 5:02 PM. On the other hand, the lowest recorded occupancy is 6 passengers, on a bus also leaving the Pentagon Building at 5:20 PM to travel along route 24P. On average, the observed bus occupancies for the eastbound and westbound directions for the Midday period are 16.0 and 16.8 persons, respectively. For the PM peak period, the average occupancies for the same directions are 20.0 and 23.0 persons. While no observations have been made for the AM peak period, it can be expected that similar occupancies as for the PM peak period would be observed, except that the flow of passengers would be reversed in direction.

Table 3.3, finally, provides a sample of bus adherence to published schedules. The table indicates schedule adherences that were observed on June 6, 2000, at the bus stops serving the eastbound and westbound traffic just east of the intersection with Walter Reed. The table indicates that there is significant variability in the time at which the buses arrive at the surveyed bus stops with respect to their scheduled published arrival times. While most of the buses arrive late, some buses do arrive earlier. The earliest arrival was 4 minutes and 35 seconds ahead of schedule, while the latest arrival was 13 minutes behind schedule. On average, buses arriving early are about 2 minutes ahead of schedule, while late buses are typically 3 minutes and 45 seconds behind schedule.

While vehicle arrival times are a function of traffic conditions upstream of the bus stops and dwell times at individual stops, and hence difficult to control tightly, the collected data indicates that bus service along Columbia could benefit from the implementation of transit priority. In this case, transit priority could allow buses that are behind schedule to catch up on their schedule and provide improved regular service along the corridor. Alternatively, denying priority of passage for buses that are ahead of schedule could bias these buses to gradually fall back into their schedule, especially where buses have to stop on the right-of-way and where bus drivers could therefore not elect to remain stopped at a bus stop until they fall back into their scheduled departure time.

Table 3.1: Observed Bus Dwell Times along Columbia Pike

Corridor Section	Period	Eastbound				Westbound				Section Average			
		Buses (veh)	Stops (veh)	Avg Dwell (sec)	Coeff. Variation	Buses (veh)	Stops (veh)	Avg Dwell (sec)	Coeff Variation	Buses (veh)	Stops (veh)	Avg Dwell (sec)	Coeff. Variation
Carlin Springs-Greenbrier	AM	--	--	--	--	--	--	--	--	--	--	--	--
	Midday	1	0	--	--	5	2	23	0.123	6	2	18.3	0.454
	PM	5	4	11.5	0.621	10	10	8.9	0.251	15	14	9.9	0.412
Greenbrier - Dinwiddie	AM	--	--	--	--	--	--	--	--	--	--	--	--
	Midday	10	8	35.8	0.446	9	6	15.7	0.587	19	14	28.5	0.575
	PM	8	8	15.5	0.467	3	3	11.3	0.310	11	11	15.0	0.462
Dinwiddie - Wakefield	AM	--	--	--	--	--	--	--	--	--	--	--	--
	Midday	8	5	27.0	0.813	3	3	13.7	0.224	11	8	20.7	0.639
	PM	8	6	16.8	0.331	2	2	19.0	0.149	10	8	16.4	0.328
Wakefield - Taylor	AM	--	--	--	--	--	--	--	--	--	--	--	--
	Midday	8	7	14.4	0.804	6	4	15.8	0.399	14	11	15.4	0.651
	PM	8	5	16.2	0.787	3	3	9.3	0.270	11	8	14.3	0.771
Taylor - Quincy	AM	--	--	--	--	--	--	--	--	--	--	--	--
	Midday	13	11	24.3	0.965	7	6	15.0	0.273	20	17	21.0	0.915
	PM	10	8	15.0	0.637	25	19	13.4	0.621	35	27	14.0	0.596
Quincy - Monroe	AM	--	--	--	--	--	--	--	--	--	--	--	--
	Midday	8	3	8.7	0.405	6	1	13.0	--	14	4	8.7	0.405
	PM	6	4	16.3	0.660	4	2	15.0	0.377	10	6	16.3	0.660
Monroe - Highland	AM	--	--	--	--	--	--	--	--	--	--	--	--
	Midday	7	7	15.4	0.557	6	4	11.0	0.445	13	11	14.8	0.528
	PM	5	4	13.8	0.161	4	4	14.5	0.542	9	8	13.8	0.208
Highland - Barton	AM	34	21	19.2	0.589	18	12	15.1	0.683	52	33	17.7	0.620
	Midday	13	9	14.8	0.851	18	17	15.2	0.491	31	26	14.6	0.823
	PM	5	4	12.0	0.379	14	14	12.4	0.413	19	18	12.8	0.936
Barton - Courthouse	AM	11	7	27.9	0.807	--	--	--	--	11	7	27.9	0.807
	Midday	11	8	19.5	0.343	6	4	7.8	0.220	17	12	16.0	0.720
	PM	8	7	10.9	0.489	13	11	13.1	0.682	21	18	12.1	0.977
Courthouse - Joyce	AM	--	--	--	--	--	--	--	--	--	--	--	--
	Midday	15	8	13.4	0.532	11	6	14.8	0.254	26	14	13.3	0.446
	PM	8	2	16.5	0.729	2	1	10.0	--	10	3	16.5	0.729
Corridor Average	AM	45	28	21.4	0.697	18	12	15.1	0.683	63	40	19.5	0.711
	Midday	94	66	20.0	0.789	77	53	14.5	0.438	171	119	17.5	0.726
	PM	71	52	14.4	0.526	83	69	12.4	0.533	154	121	13.3	0.534

[1] Average dwell time and coefficient of variation only consider stopping buses

Table 3.2: Observed Bus Occupancies along Columbia Pike

Period	Direction	Route	Time	Intersection	Occupancy (persons)
Midday	Eastbound	16J	11:13	Courthouse	10
		16J	11:21	Pentagon	16
		16J	12:12	Jefferson	11
		16J	12:29	Navy Annex	25
		16J	1:03	Jefferson	17
		16J	1:09	Highland	17
	Westbound	16D	11:34	Pentagon	18
		16D	11:53	Carlin Spring	12
		16D	12:34	Navy Annex	16
		16D	12:51	Carlin Spring	21
PM Peak	Eastbound	16A	4:16	Carlin Spring	25
		16A	4:38	Pentagon	16
		16A	6:23	Jefferson	16
		16A	6:40	Highland	23
	Westbound	16J	3:54	Walter Reed	37
		16J	4:08	Jefferson	24
		16J	4:42	Pentagon	33
		16F	4:45	Pentagon	18
		16X	4:47	Pentagon	14
		16G	4:50	Pentagon	30
		16U	4:52	Pentagon	23
		16W	4:56	Pentagon	24
		16D	5:02	Pentagon	63
		16F	4:57	Pentagon	23
		16F	5:05	Pentagon	25
		16X	5:07	Pentagon	14
		16J	5:08	Pentagon	11
		16F	5:14	Pentagon	19
		16W	5:16	Pentagon	31
		24P	5:19	Pentagon	6
		16F	5:20	Pentagon	27
		16U	5:22	Pentagon	11
		16G	5:25	Pentagon	31
		16G	5:45	Dinwiddle	14
		16A	5:53	Dinwiddle	19
		16D	6:19	Jefferson	10

Table 3.3: Observed Bus Schedule Adherence at Bus Stops near Walter Reed

Period	Direction	Route	Arrival Time	Scheduled Arrival Time	Minutes Ahead	Minutes Late
AM Peak	Eastbound	16A	7:21:49	7:24:00	2:11	
		16A	8:34:56	8:27:00		7:56
		16D	8:08:03	7:55:00		13:03
		16D	9:02:05	8:57:00		5:05
		16G	7:09:17	7:06:00		3:17
		16G	7:41:03	7:35:00		6:03
		16G	8:39:46	8:38:00		1:46
		16J	7:46:12	7:45:00		1:12
		16J	8:17:38	8:17:00		0:38
		16J	8:50:32	8:47:00		3:32
		16W	7:32:00	7:30:00		2:00
		16W	7:32:20	7:34:00	1:40	
		16W	7:55:00	7:51:00		4:00
		16W	8:13:20	8:12:00		1:20
		16W	8:38:20	8:32:00		6:20
		16W	8:54:03	8:53:00		1:03
		16X	7:45:55	7:43:00		2:55
		16X	8:06:36	7:55:00		11:36
		16X	8:17:09	8:21:00	3:51	
		16X	8:47:04	8:42:00		5:04
Midday	Eastbound	16A	11:28:05	11:27:00		1:05
		16A	12:22:25	12:27:00	4:35	
		16C	11:43:46	11:42:00		1:46
		16C	12:43:12	12:42:00		1:12
		16D	12:56:40	12:57:00	0:20	
		16J	11:08:17	11:12:00	3:43	
		16J	12:11:46	12:12:00	0:14	
		24M	11:25:52	11:21:00		4:52
		24M	12:35:46	12:31:00		4:46
	Westbound	16A	11:11:37	11:09:00		2:37
		16A	12:10:43	12:09:00		1:43
		16C	11:54:07	11:54:00		0:07
		16C	12:53:45	12:54:00	0:15	
		16J	11:30:23	11:24:00		6:23
		16J	12:26:28	12:24:00		2:28
		24M	11:51:24	11:49:00		2:24

3.2 Modeling Approach

For this study, the INTEGRATION microscopic traffic simulation model (M. Van Aerde and Associates, 2000a, 2000b) was selected to conduct the analysis. This model, which was conceived as an integrated simulation and traffic assignment model, performs simulations by explicitly tracking the movement of individual vehicles within a transportation network every deci-second. This detailed tracking of vehicle movements allows, among other things, the model to conduct detailed analyses of lane changing movements, shock wave propagations along transportation links, as well as gap acceptance, merge and weaving behaviors at intersections and freeway entrances and exits. The microscopic modeling featured by the software also permits considerable flexibility in representing spatial variations in traffic conditions, in addition to considering time variations in traffic demands, vehicle routings, link capacities and traffic controls without the need to pre-define common time-slice durations. This implies that the model is not restricted to hold departure rates, signal timings, incident severities and durations, and even traffic routings at constant settings for any period of time. Finally, in addition to estimating stops and delay, the model also possesses internal routines that directly estimate the fuel consumed by individual vehicles, as well as the emissions of hydrocarbon (HC), carbon monoxide (CO) and oxides of nitrogen (NO_x) that are produced by these vehicles. Similar to the tracking of vehicle movements, these parameters are estimated on a second-by-second basis based on each vehicle's instantaneous speed and acceleration levels.

This section describes the modeling approach that was followed, first to generate an INTEGRATION simulation model of the study corridor, and then to evaluate the potential benefits of providing priority to transit vehicles traveling along the corridor. Specifically, the section successively presents the overall methodology of the simulation study, the data that were required to build the simulation model, the approach that was followed to model traffic demand within the simulation environment, and the various scenarios that were developed to evaluate the potential benefits of alternative transit priority strategies and adaptive signal control strategies.

3.2.1 Methodology of Simulation Study

Figure 3.9 illustrates the overall methodology of the simulation study. As indicated, the methodology was comprised of four major steps. In the first step, the geometry of the study corridor was defined in terms of nodes and links in a format that was consistent with the input requirements of the INTEGRATION simulation software. Subsequently, the Origin-Destination demand was calibrated based on field observed link flow and turning movement counts at a number of signalized intersections. Specifically, the Origin-Destination (O-D) demand was estimated utilizing a maximum likelihood synthetic O-D tool (the QUEENSOD model), which was explicitly developed to support the INTEGRATION model (Van Aerde *et al.*, 1993; M. Van Aerde and Associates, 1998*)*. Using the modeled network and estimated traffic demand, the INTEGRATION simulation software was then used to simulate the effects of implementing alternative transit priority and adaptive signal control schemes along the study corridor. Finally, upon completion of the simulations, the benefits of the various priority and adaptive schemes were evaluated using a number of measures of effectiveness that included vehicle delay, passenger delay, vehicle stops, fuel consumption, and emissions.

3.2.2 Required Input Data

To develop an INTEGRATION simulation model, a series of information on the transportation network that is to be modeled and simulated must be provided. For the analysis considered in this project, the following data were coded:

General Network geometry: Modeling of the transportation network in terms of nodes, links and origin-destination traffic zones.

Individual link geometry: Characterization of each defined transportation link in the simulation network in terms of length, number of lanes, lane striping, speed/flow relationship, and saturation flow rate. While not required, grades were also provided for completeness of the modeling.

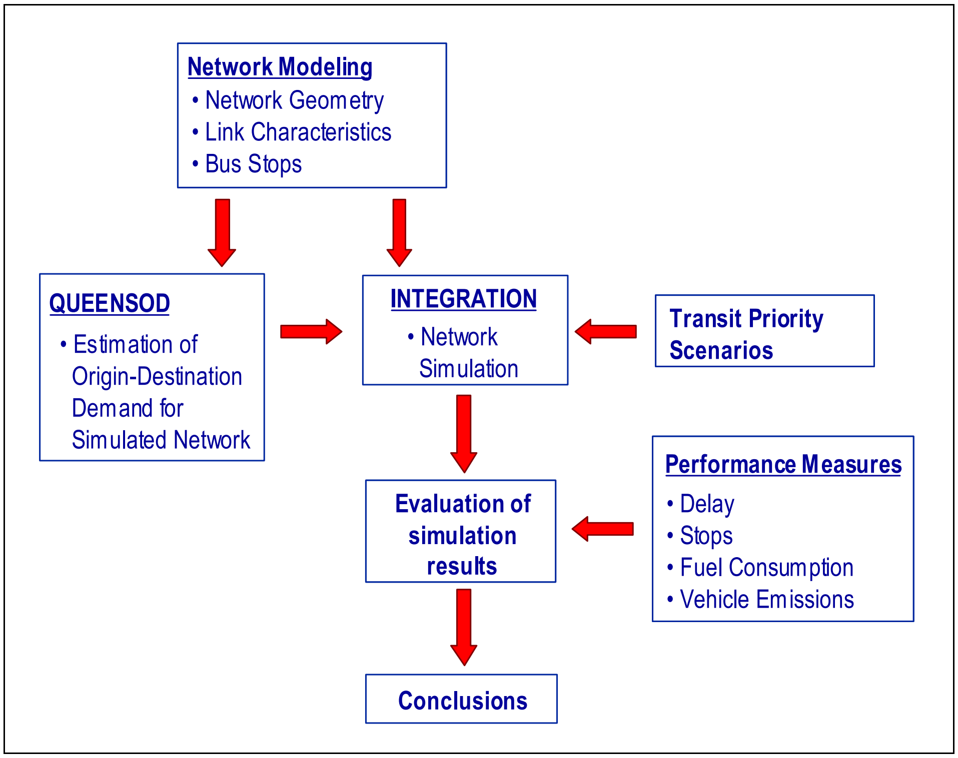

Figure 3.9: Study Methodology

Traffic signal control: Definition of signal control at individual intersections in terms of minimum and maximum allowed cycle times, number of phases used by the signal control, phase sequence, signal offset with respect to a reference phase at a given master intersection, duration of the green interval and lost time for each defined phase, and whether the operation is fixed or adaptive at pre-set intervals.

Demand data: Definition of both vehicular and transit traffic demands in terms of an origin-destination table indicating the flow rates between each pair of traffic zones.

Bus stops: Localization of bus stops along modeled transportation links and characterization of transit activities at each bus stop in terms of vehicle types servicing the stop and distribution of individual dwell times.

3.2.3 Demand Modeling Approach

Figure 3.10 illustrates the approach used by the QUEENSOD model to estimate origin-destination traffic demands for a given transportation network. As indicated in the figure, the model estimates these origin-destination demands based on observed link traffic flows, observed link turning movement counts, and an initial demand seed.

Specifically, the demand estimation process starts, after having read the input data, with the building of a first all-or-nothing travel tree from every origin zone to every destination zone in the modeled transportation network. This is done on the basis of the link travel times defined in the network modeling. The building of this tree ensures that a feasible path exists from every origin to every destination. Once the tree has been built, the seed demand that was provided with the input data is applied to the modeled transportation network. This yields a first set of flows for each link in the network. Following this first loading, a number of iterations in which the link flows are adjusted based on their differences with the corresponding observed flows are then carried out to find the overall simulated traffic demand that best matches the observed link traffic flows.

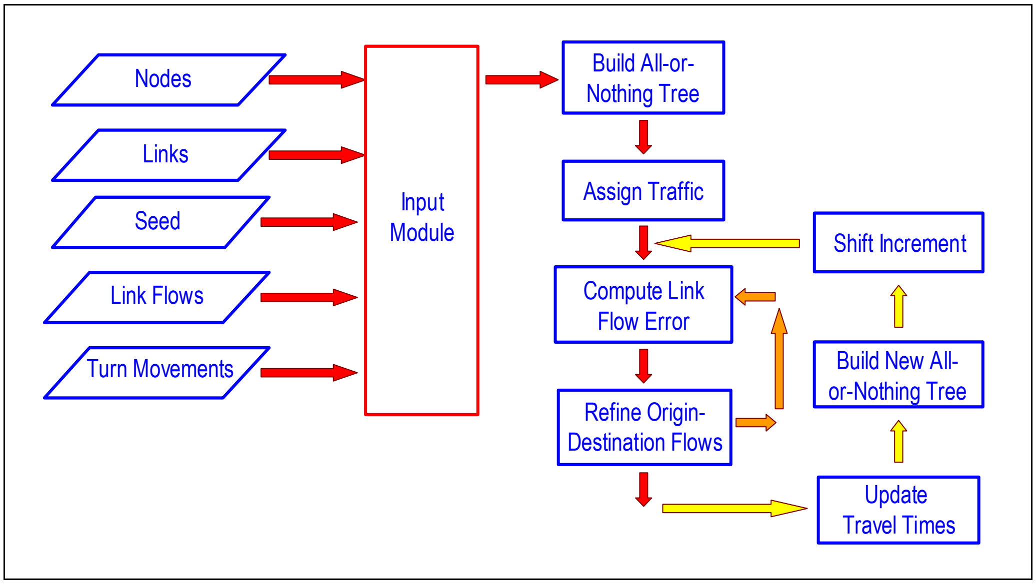

Figure 3.10: Generation of Origin-Destination Demand with QUEENSOD

Following this first demand estimation process, a second optimization loop is applied to further increase the match between synthetic and observed link flows. In this second loop, observed link travel times are decreased on links with underestimated synthetic flows in order to make them more attractive, and increased on links with overestimated synthetic flows to make them less attractive. After having adjusted the observed link travel times, a second all-or-nothing tree is built and a proportion of traffic that will use this new tree to determine its path through the network instead of the first one, known as the tree weight, is also determined based on a function that incrementally increases this proportion from 0 to 100% using a user-defined step-size. For each tree weighting, the best origin-destination demand is then found and the resulting residual link flow error recorded. The weight associated with the second all-or-nothing tree is then incrementally increased until the current tree and tree weight combination results in higher residual link flow error, i.e., less optimal results, than the previous combination.

Once the second iteration has stopped, the link travel times are adjusted once more and another all-or-nothing travel tree is built. The dual-loop iterative process described above is then repeated until a user-specified number of trees have been built. After the last tree is built, the origin-destination flows produced by the last iteration are returned as the best synthetic origin-destination demand based on the observed traffic demand data provided as input.

3.2.4 Evaluation Scenarios

In order to evaluate the potential benefits of implementing transit priority along Columbia Pike and its integration with adaptive signal control, three specific evaluation periods were identified based on traffic flow observations along the corridor:

- **AM Peak Period (7:00 AM – 9:00 AM):** Period characterized with high flows, mainly eastbound and northbound oriented.
- **Midday Period (11:00 AM – 1:00 PM):** Period characterized with medium flows, with no apparent directional behavior.
- **PM Peak Period (4:30 PM – 6:30 PM):** Period characterized with high flows, mainly westbound and southbound oriented.

To fully evaluate the potential benefits of implementing transit priority and its integration with adaptive signal control along the corridor, six priority scenarios were also developed:

- **Base Scenario:** No priority offered to any vehicle.
- **Priority Scenario 1:** Priority offered between Dinwiddie and Quinn streets only to express buses traveling along Columbia Pike.
- **Priority Scenario 2:** Priority offered between Dinwiddie and Quinn streets only to regular buses traveling along Columbia Pike.
- **Priority Scenario 3:** Priority offered between Dinwiddie and Quinn streets to all buses traveling primarily along Columbia Pike only.
- **Priority Scenario 4:** Priority offered between Dinwiddie and Quinn streets to buses traveling primarily on streets crossing Columbia Pike.
- **Priority Scenario 5:** Priority between Dinwiddie and Quinn streets to all buses traveling along Columbia Pike and on streets crossing the arterial roadway.

Finally, in evaluating the various traffic signal control options and their integration with transit priority along the study corridor, six signal scenarios were further developed, which included:

- **Signal Scenario 1 – Fixed-time Control:** Simulation of current MONARC fixed timing plans for all intersections along the corridor.
- **Signal Scenario 2 – Observed SCOOT Control:** For SCOOT-controlled intersection, simulation of the average signal timings that were implemented by the SCOOT system at each intersection within a series of 15-minute intervals on June 13 and 14, 2000; for other intersections, simulation of current MONARC fixed timing plans.
- **Signal Scenario 3 – INTEGRATION Splits:** Similar to Signal Scenario 1, but allows the phase split at all SCOOT-controlled intersections to be adjusted at 5-minute intervals by the signal optimization routine embedded within the INTEGRATION model.
- **Signal Scenario 4 – INTEGRATION Splits and Offsets:** Similar to Signal Scenario 1, but allows the phase split at all SCOOT-controlled intersections to be adjusted at 5-minute intervals by the INTEGRATION signal optimization routines. The offset is optimized each cycle length to minimize a network-wide performance index.
- **Signal Scenario 5 – INTEGRATION Splits and Cycle:** Similar to Signal Scenario 1, but allows the phase split and signal cycle of all SCOOT-controlled intersections to be adjusted at 5-minute intervals by the INTEGRATION signal optimization routines (non-coordinated adaptive control).
- **Signal Scenario 6 – INTEGRATION Control:** Simulates non-coordinated SCOOT control along the corridor by allowing the INTEGRATION signal optimization routines to adjust the signal cycle length, phase split and signal offset at all SCOOT-controlled intersections. Cycle length and phase splits are adjusted every 5 minutes, while offsets are adjusted every cycle length.

3.3 Data Collection Efforts

To obtain the information required to develop a simulation model of the study corridor, four major data collection efforts were organized. These efforts were conducted in June and October of 2000 and are described below.

The first data collection effort to take place constituted manual traffic counts at the busiest intersections along the corridor. As indicated in Figure 3.11, counts were conducted at the intersections with Carlin Spring, Four Mile Run, Buchanan, George Mason, Glebe, Walter Reed, and Joyce, as well as at all entrance and exit ramps at the interchange with the Washington Boulevard. Counts at the intersections with Carlin Spring, Buchanan and George Mason were conducted on Tuesday, June 6, while the counts at Glebe, Walter Reed and Joyce were conducted on Wednesday, June 7, and the counts at Four Mile Run and Washington Boulevard on Thursday, June 8. No information was collected on Monday or Friday, as studies have shown that these days are often not reflective of typical weekday traffic conditions (Rakha and Van Aerde, 1995). During the counts, through, left-turning and right-turning movements were observed and compiled for each intersection. Compilations were done for three control periods using 5-minute count intervals. The first period covered the morning travel period and extended from 7:00 to 9:00 AM. The second period covered the noon travel period from 11:00 AM to 1:00 PM. Finally, the third period covered the PM peak travel period from 4:30 to 6:30 PM.

In addition to manual counts, additional flow information was obtained from the SCOOT detectors installed along the corridor between Dinwiddie and Quinn. Figure 3.11 illustrates more specifically the links for which SCOOT traffic data were provided by the Arlington County Department of Public Works. As illustrated, flow information was obtained for all the intersections between Dinwiddie and Quinn, inclusively. This allowed both manual and SCOOT traffic counts to be collected for the intersections with Four Mile Run, Buchanan, George Mason, Glebe, Walter Reed and Quinn. In this case, the data that were provided by the Arlington County Department of Public Works consisted of traffic flow diagrams showing 15-minute traffic counts for each intersection approach over a period of three consecutive days extending from June 12 to June 14, 2000. An example of these counts was illustrated in Figure 3.5 in Section 2.2. However, contrary to the manual counts, these counts provided no information about turning movements at signalized intersections. Since SCOOT detectors are typically installed at the exit of the upstream intersection, they can only provide information about total flow counts on each intersection approach.

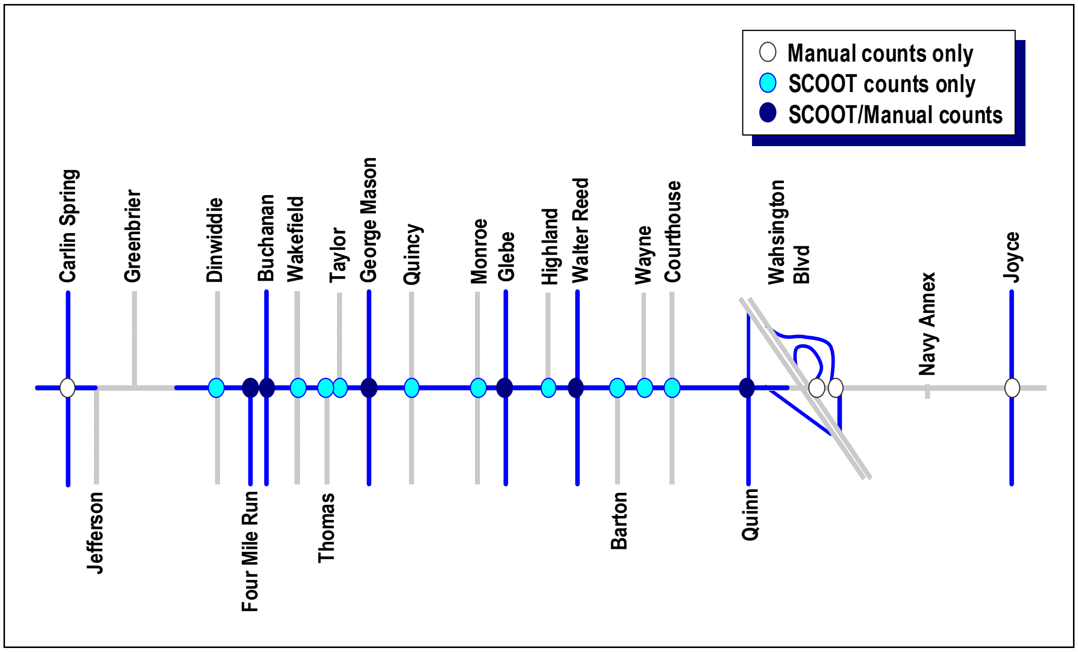

Figure 3.11: Traffic Flow Information Sources

In addition to the manual and SCOOT traffic counts, information about traffic flow characteristics was also obtained from probe vehicles equipped with Trimble Placer 450/455 GPS receivers (Trimble Navigation Ltd, 1996). By driving each GPS-equipped vehicle along the study corridor and recording its position and speed every second, information could be obtained about typical traffic conditions on each segment of the corridor. Furthermore, by marking the instant the vehicle entered each intersection and passed each bus stop, relatively accurate information was obtained on the position (latitude, longitude, altitude) of each intersection and bus stop location along the corridor. Information about transit activity (bus speeds, dwell times) was also obtained by closely following buses traveling along the corridor. For each direction of travel along Columbia Pike, 11 runs aimed at characterizing traffic conditions were made during the AM peak, Midday and PM peak control periods between June 6 and June 8, 2000. 13 other eastbound and westbound runs were also executed in order to locate signalized intersections along the corridor. Seven additional runs aimed at characterizing transit operations and locate bus stops along the corridor were made on June 8.

To further characterize transit operations, bus dwell times were collected by observers and from videotapes of transit activities at specific bus stops in June and October 2000. Table 3.4 indicates the details of the data collection activities. Since not all bus stops could be surveyed within the allocated time and budget, information was collected at representative bus stops within each section of the corridor. For this compilation, bus dwell times were measured from the moment a bus arrived at the stop up to the moment it left the stop or was ready to leave in cases in which traffic conditions prevented an immediate departure. A small sample of bus occupancy data was also collected on June 6 by observers sitting at various stops and riding buses so as to obtain rough estimates of bus occupancy in the AM peak, Midday and PM peak control periods.

Table 3.4: Bus Dwell Time Data Collection Efforts

Bus Stop	**Period**	**Direction**		**Date**	**Source**
		EB	**WB**		
Jefferson	PM	4	9	October 3, 10	Observer
George Mason	Midday	5	4	October 12	Observer
	PM	13	23	June 7, October 4	Video
Walter Reed	AM	34	18	June 6	Observer
	Midday	10	9	June 6	Observer
	PM	4	9	October 12	Observer
Courthouse	AM	11		June 7	Video
	Midday	3		June 7	Video
	PM	2	9	October 4, 11	Observer

Other relevant information that were collected between June and October 2000 to characterize the study corridor include the speed limit and lane striping on each intersection approach, the length of left-turn and right-turn bays, and the signal timings used to control traffic along the corridor. In the case of the signal timings, no field observations were required as the signal timings for all intersections along the corridor were directly provided by the Arlington County Department of Public Works. These data included:

- The MONARC fixed signal timing plans for all intersections between Carlin Springs and Joyce.
- The SCOOT signal timings that were implemented over a 24-hour period on June 13 at all the intersections between Dinwiddie and Highland, inclusively.
- The SCOOT signal timings that were implemented over a 24-hour period on June 14 at all the intersections between Walter Reed and Quinn, inclusively.

3.4 Simulation Model Setup

This section presents the main elements of the INTEGRATION simulation model setup. Specifically, the section presents an overlook of the modeled transportation network, a detailed description of how the simulated traffic demand was calibrated to reflect existing traffic conditions along the study corridor, and descriptions of how traffic signal and transit operations were modeled along the corridor.

3.4.1 Geometric Layout

For this study, the network of Figure 3.2 was coded in the INTEGRATION model. The resulting simulation network includes a total of 243 nodes and 239 links. For each link, information about link length, free-flow speed, grade, turn prohibition, and lane striping were coded based on collected field data. Since saturation flow rates were not part of the collected data, a standard rate of 1800 veh/h was assumed for all simulated links.

Figure 3.12 further illustrates how the instantaneous GPS speed measurements that were made along Columbia Pike were used to determine the speed at which vehicles typically travel on each segment of the corridor when they are not constrained by other traffic. Based on the speed measurements that were made for the AM peak, Midday, and PM peak periods, as well as on geometrical considerations, the free flow speeds shown in Figure 3.12 were coded in the INTEGRATION model for each segment of the simulation corridor.

As it can be observed in both diagrams of Figure 3.12, the free-flow speeds that were determined vary along the corridor between 60 and 70 km/h (37 to 44 mph). As indicated, these speeds are much higher than the posted speed limits of 48 and 58 km/h (30 and 35 mph). This observation has an important impact on the conduction of the simulation study, as it indicates that the use of posted speed limits in the simulation would not accurately represent existing traffic conditions along the corridor. If posted speed limits were used, it would then be assumed that vehicles take more time than they do in reality to travel from one intersection to the other. When considering providing priority to transit vehicles, such an assumption could then lead to the implementation of longer than required green extensions or to the implementation of green recalls that are not long enough to prevent the approaching buses to stop, even briefly, at the intersection stop lines. The accurate measurement of free-speed is also important for the estimation of signal offsets and to ensure that the simulated conditions are consistent with the observed field conditions.

3.4.2 Traffic Demand Calibration

Figure 3.13 illustrates over identical scales the general traffic demand that was generated by the QUEENSOD model for the AM, Midday, and PM peak periods based traffic and turning movement counts. As illustrated, the traffic demands were generated as a series of 15-minute traffic demands to allow the INTEGRATION model to simulate observed changes in traffic demand within each control period.

In particular, it is observed in Figure 3.13 that the generated demands are not constant over time and differ from one period to the other. For the AM peak period, the simulated demand increases gradually from 7:00 and 7:45 AM, then remains relatively constant between 7:45 and 8:30, and finally decreases gradually between 8:30 and 9:00 AM. Within this period, the demand varies between 2800 and 3500 trips/15 minutes. For the Midday period, there is a continuous increase in simulated demand over the entire period. The demand is also somewhat reduced when compared to the AM peak period, ranging between 2300 and 2900 trips/15 minutes. Finally, for the PM peak, the simulated demand slightly increases from 4:30 and 5:15 PM, and then remains stable until 5:45 PM before decreasing slowly between 5:45 and 6:30 PM. This period also shows a demand ranging between 3600 and 4000 trips/15 minutes, which is the highest of all the simulation periods.

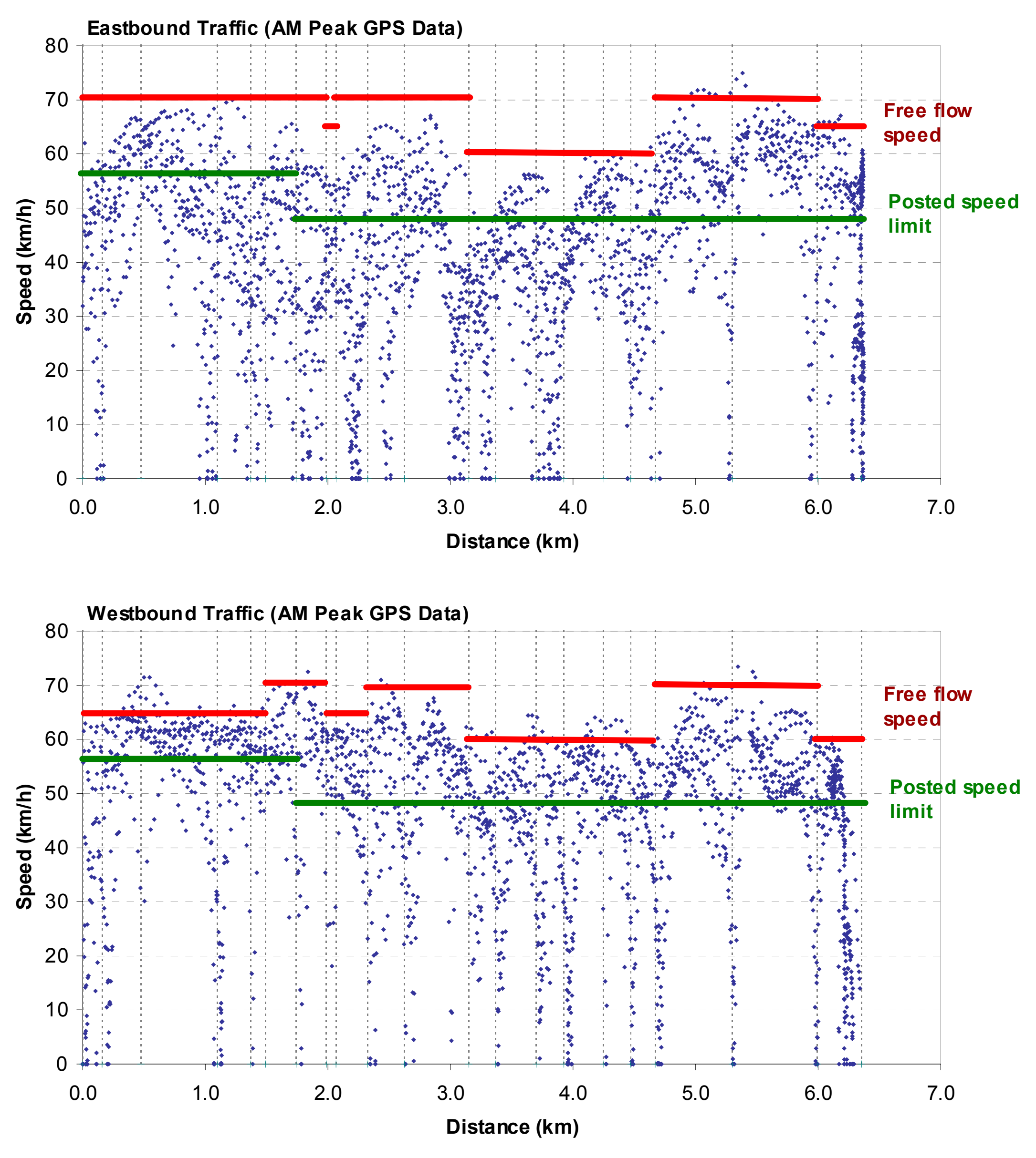

Figure 3.12: Observed Free Flow Speeds along Study Corridor (AM Peak Period)

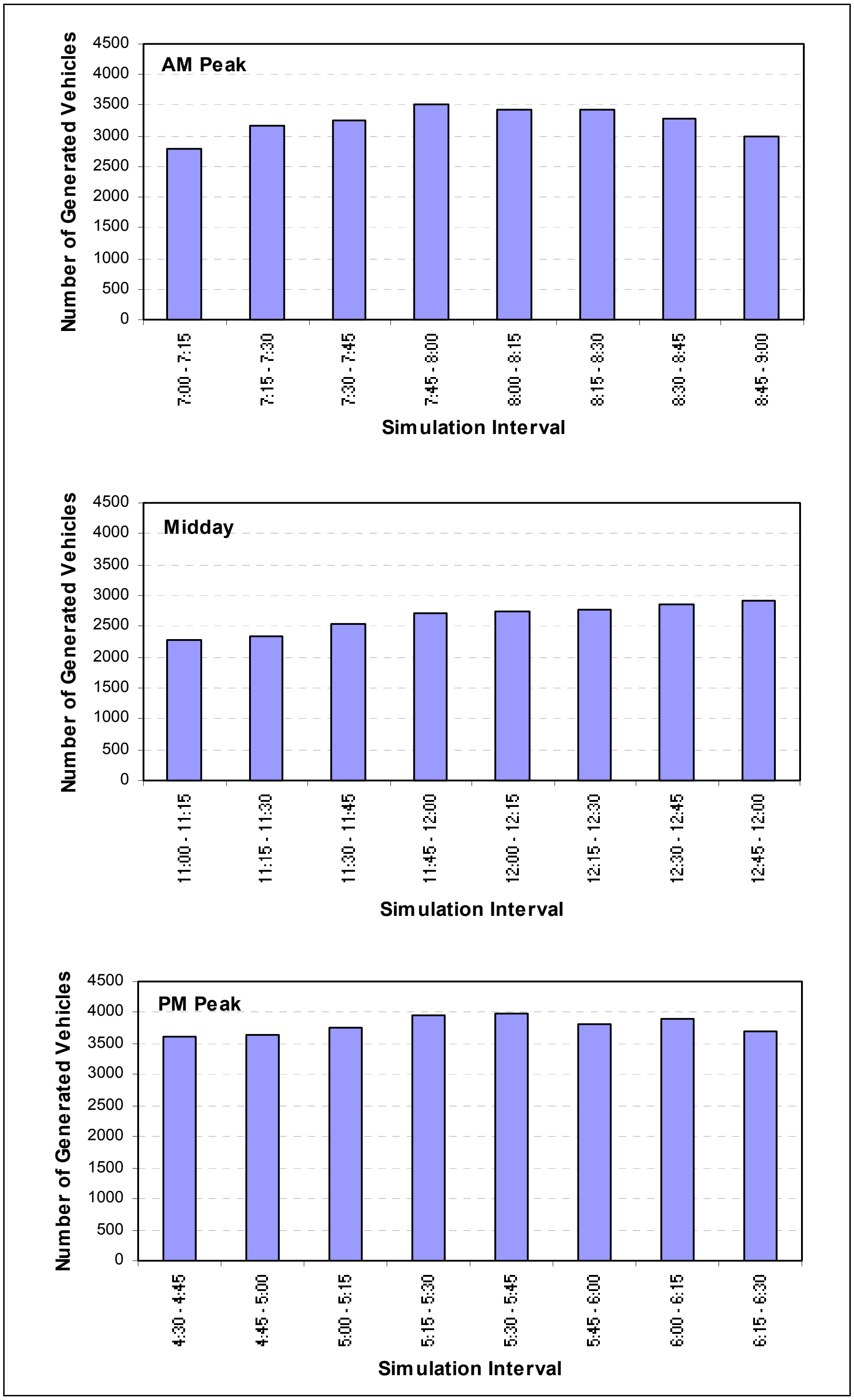

Figure 3.13: Simulated Traffic Demands for the AM Peak, Midday and PM Peak Periods

To generate the demand for each 15-minute simulation interval, three optimization methods were considered. The first method generated optimum O-D tables by minimizing the squared error between the observed and estimated synthetic flows for each link for which flow observations were available. The second method minimized the relative error between the observed and synthetic link flows, while third method minimized the Poisson error.

A comparison between the observed and synthetic link flows produced by all three optimization methods for a single 15-minute interval during the AM peak period is shown in Figure 3.14. As illustrated, none of the three methods resulted in a perfect match between the observed and synthetic flows. In particular, increasing errors are observed with increasing flow levels. It is also observed that the largest errors are associated with links for which flow information was obtained from the manual counts. This is explained by the fact that the manual counts generally yielded much larger flows than the SCOOT detectors, causing some inconstancies to exist between the manual counts and SCOOT detector flows. This difference is illustrated in Figure 3.15, which compares the SCOOT flows to the manual counts for all simulation links for which both types of flow data are available. In this case, since the SCOOT flow information covered a three-day period and since the manual counts comprised only data covering a single day of observation, greater confidence was put on the validity of the SCOOT flow data. However, since the SCOOT data did not provide any information about turning percentage at signalized intersections, the manual traffic counts still had to be used in the O-D demand estimation process, thus causing the errors shown in Figure 3.14 to appear. It should also be noted at this point that the SCOOT flow data were collected a week after the manual counts were conducted. The week that the SCOOT data were collected was the last day of public school operations and thus could explain the lower SCOOT demand compared to the manual counts.

After inspection of the optimization results for all intervals, it was determined that the least relative error optimization method provided the best results for the study network. In particular, this method resulted in the best fit between observed and synthetic flows for links carrying low levels of flow. The advantage of using this method is, for instance, that an error of 10 vehicles on a link carrying 100 vehicles per hour will have the same importance as an error of 100 vehicles on a link carrying 1000 vehicles per hour. Since there are proportionally more links carrying low flows within the simulated network than links carrying high flows, it was determined that the accuracy of flows over a large number of links was more important than accuracy of flows for a small number of links carrying high volumes. Furthermore, given that the low flows are typically for turning movements, it was important to minimize errors between simulated and field conditions for these movements.

The choice of the least relative error optimization method to generate the O-D demand to simulate was validated by simulating the traffic demand that was estimated by the method for the AM, Midday and PM peak periods. The results of these simulations are shown in Table 3.5, Table 3.6, and Table 3.7, which compare for all the intersections covered by the manual counts the total simulated flow to the total counted flow over the corresponding two-hour simulation period. To emphasize the differences between the counted and simulated flows, differences of more than 100 vehicles have been shaded in the tables. As can be observed, there is for each control period a general agreement between the simulated and observed flows. In each table, the largest differences are found for the Columbia Pike approaches to intersections with Buchanan, George Mason, Glebe and Walter Reed. For these approaches, the observed errors are again explained by the fact that the SCOOT flows for these approaches were much lower than the manual counts. Since there are more links throughout the coded network for which SCOOT flow data were available than links with manual count data, it was therefore expected that the QUEENSOD model would tend to produce synthetic O-D demand tables that reflect more the SCOOT flows than the manual count flows.

Figure 3.16 and Figure 3.17 provide further validation of the synthetic O-D demands that were generated by the QUEENSOD model. The figures compare for the intersections with George Mason and Glebe the flows that were generated by QUEENSOD to the flows that were provided by the SCOOT detectors. While the figures indicate some differences between the simulated and observed flows, the general trends of demand variations over time are clearly replicated, particularly for the intersection with Glebe. In both cases, the differences that are observed between the simulated and SCOOT flows are again primarily the results of the discrepancies between the SCOOT detector and manual count data that were used to generate the flows.

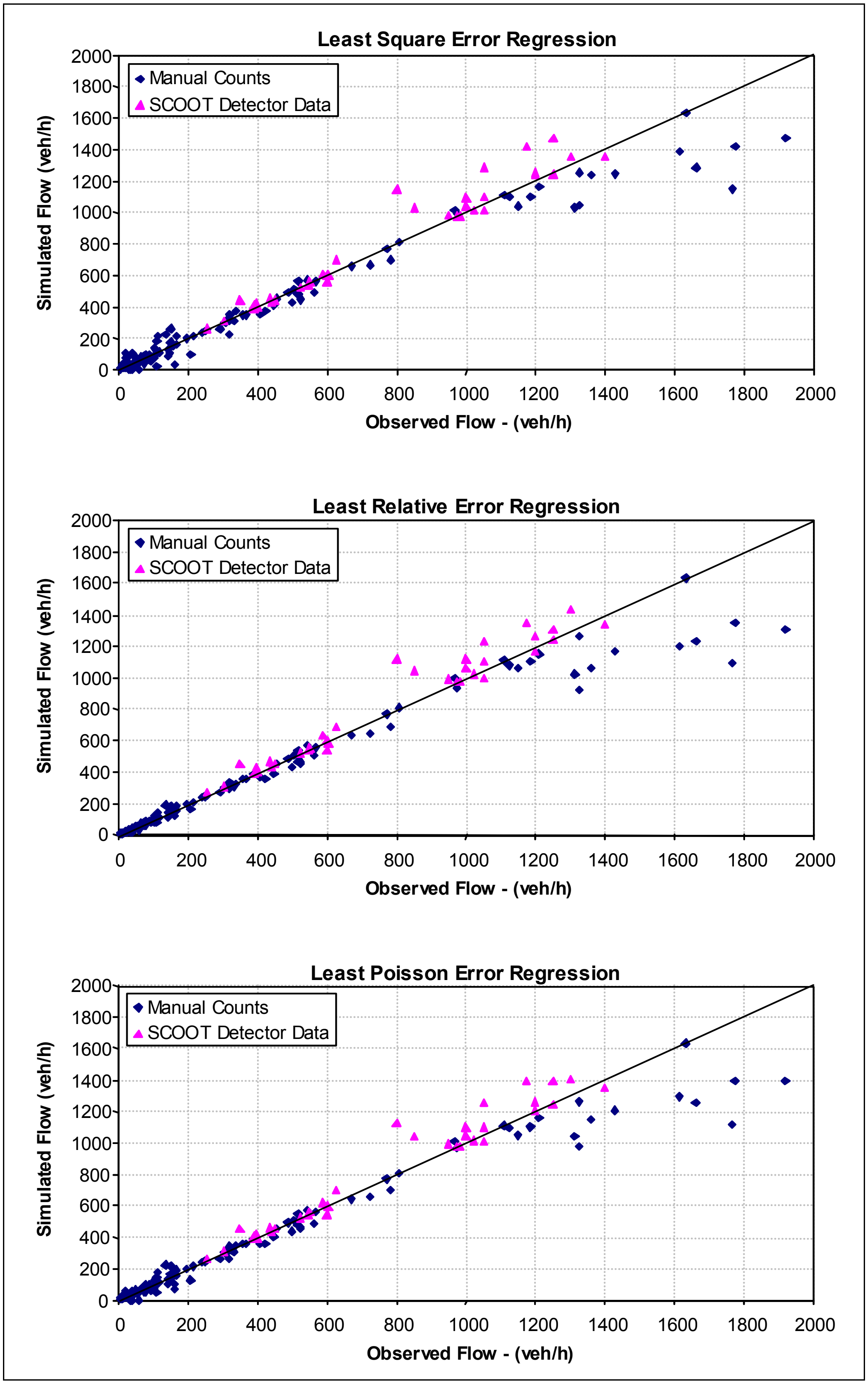

Figure 3.14: Simulated and Observed Flows (8:00-8:15 AM Interval)

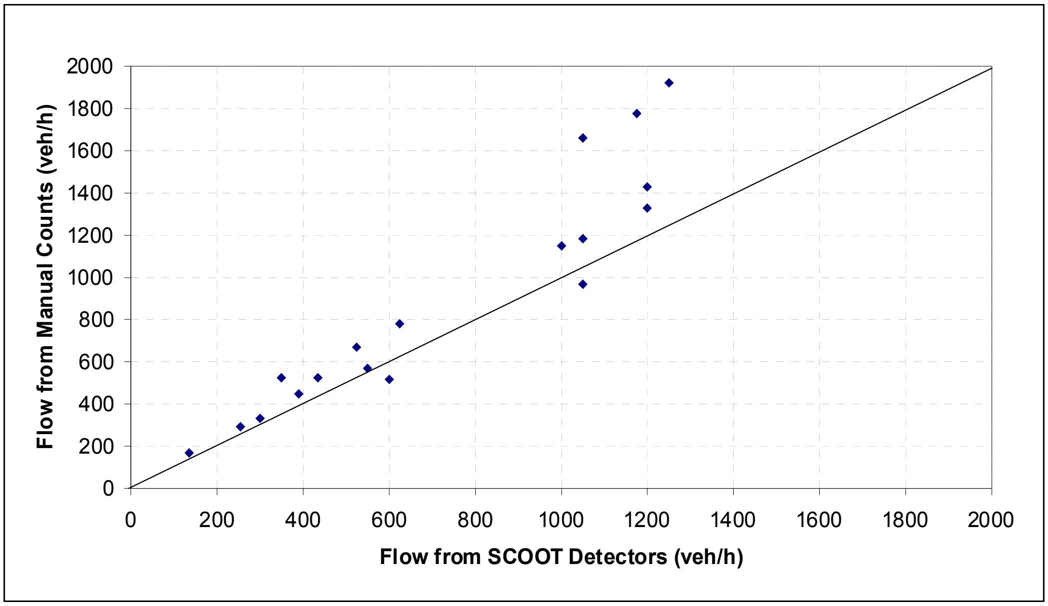

Figure 3.15: Comparison of Manual and SCOOT Traffic Counts

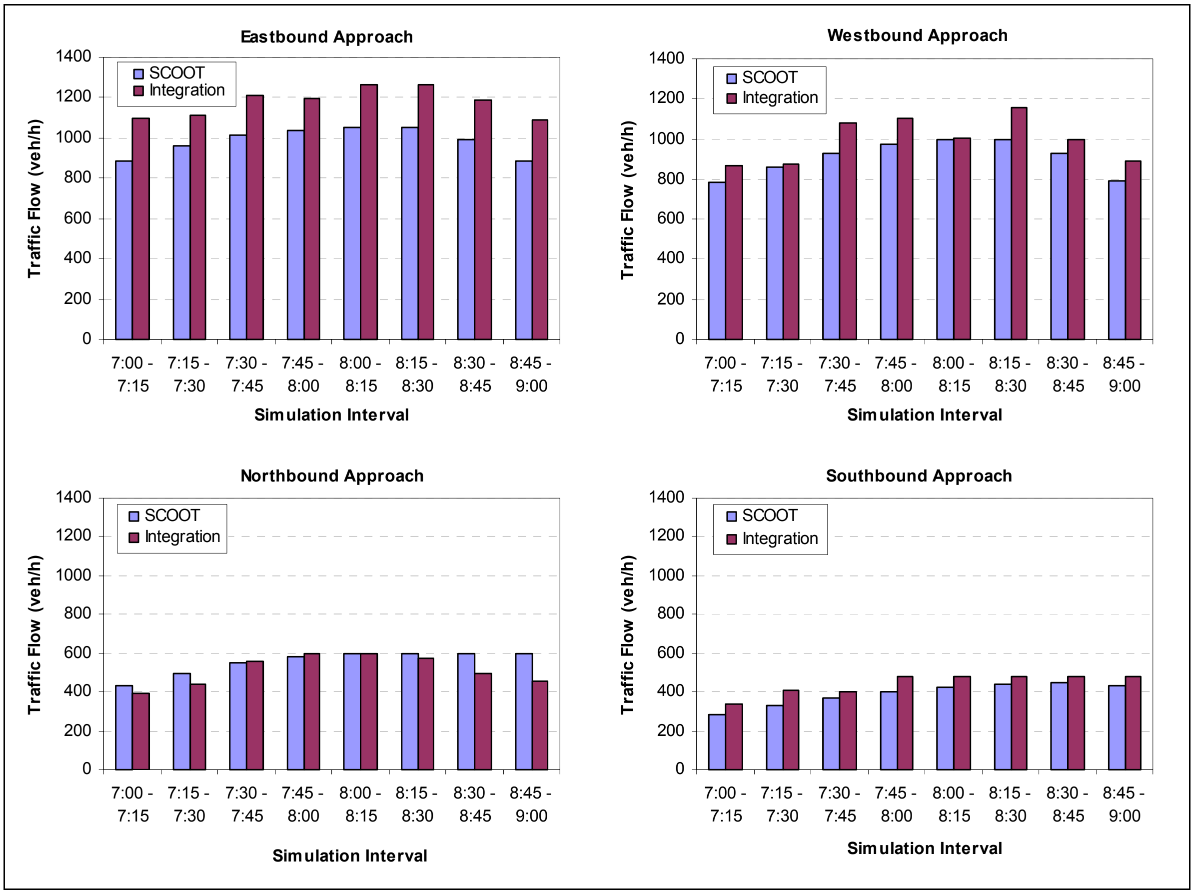

Figure 3.16: AM Peak Simulated Flows and SCOOT Traffic Counts for George Mason

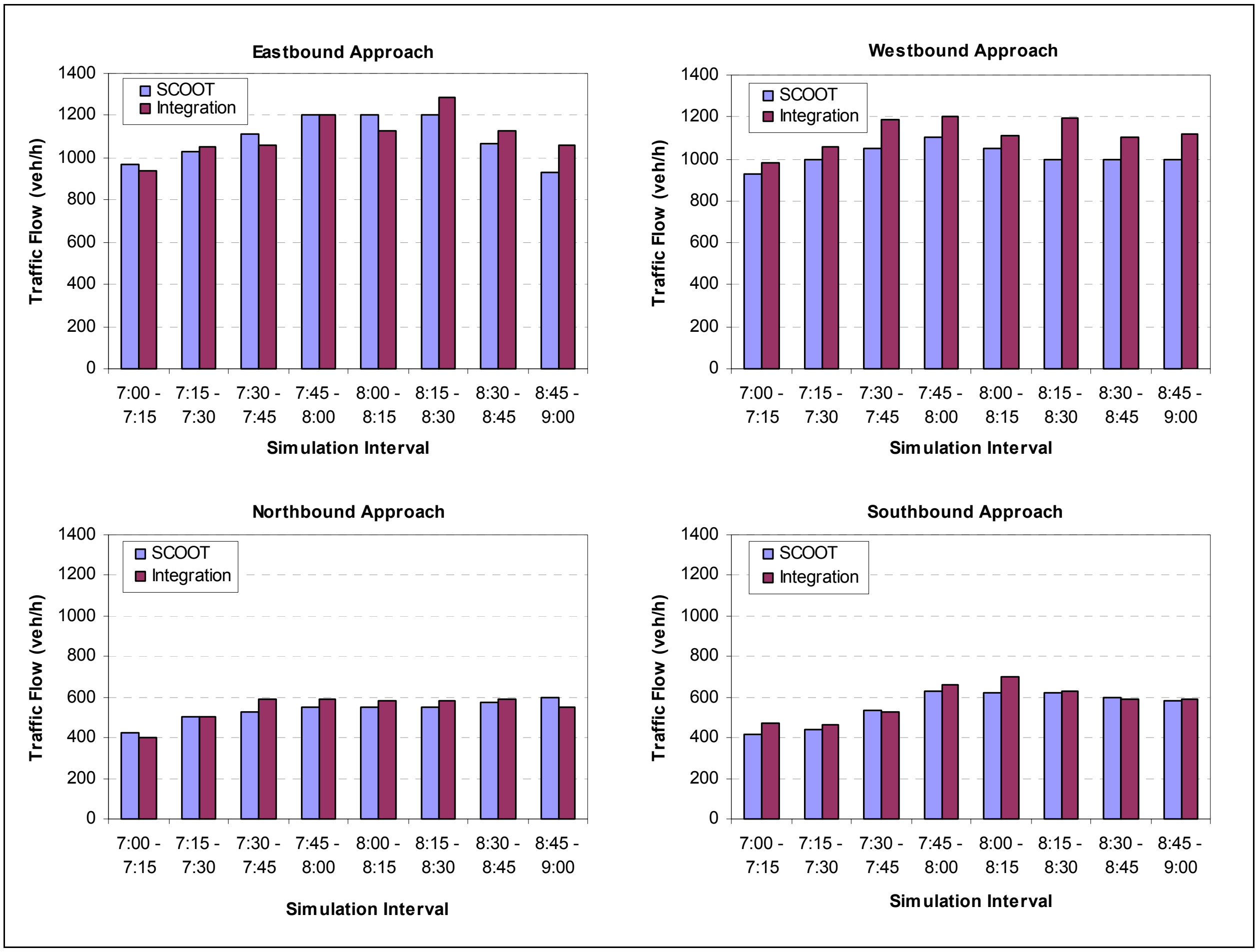

Figure 3.17: AM Peak Simulated Flows and SCOOT Traffic Counts for Glebe

Table 3.5: Comparison of Total Observed and Simulated Flows for AM Peak Period

	Columbia Pike Eastbound				Columbia Pike Westbound				Cross-Street Southbound				Cross-Street Nortbound			
	Total	L	T	R	Total	L	T	R	Total	L	T	R	Total	L	T	R
	Carling Springs															
Manual Count	3086	936	2109	41	1349	115	843	391	1141	360	404	377	1040	146	759	135
Simulation	3108	884	2170	54	1332	112	847	373	1164	364	422	378	1041	147	761	133
Difference	22	-52	61	13	-17	-3	4	-18	23	4	18	1	1	1	2	-2
	Four Mile Run															
Manual Count	274	--	--	274	51	51	--	--	--	--	--	--	437	274	--	163
Simulation	303	--	--	303	35	35	--	--	--	--	--	--	469	320	--	149
Difference	29	--	--	29	-16	-16	--	--	--	--	--	--	32	46	--	-14
	Buchanan															
Manual Count	3215	215	2934	66	2958	13	861	40	378	50	45	110	288	84	43	40
Simulation	2326	294	1932	100	2445	21	705	30	338	37	47	96	269	75	44	26
Difference	-889	79	-1002	34	-513	8	-156	-10	-40	-13	2	-14	-19	-9	1	-14
	George Mason															
Manual Count	3097	595	2444	58	1014	106	687	221	983	134	729	120	2346	32	2003	311
Simulation	2331	525	1738	68	1008	117	653	238	870	107	665	98	1989	33	1734	222
Difference	-766	-70	-706	10	-6	11	-34	17	-113	-27	-64	-22	-357	1	-269	-89
	Glebe															
Manual Count	2896	--	2707	189	1215	53	856	306	1213	--	1136	77	2544	--	2449	95
Simulation	2153	--	1899	254	1106	49	775	282	1151	--	1069	82	2240	--	2198	42
Difference	-743	--	-808	65	-109	-4	-81	-24	-62	--	-67	5	-304	--	-251	-53
	Walter Reed															
Manual Count	2618	179	2400	39	1267	136	1033	98	606	89	384	133	1926	158	1162	606
Simulation	2334	159	2121	54	1169	147	917	105	577	89	376	112	1878	147	1141	590
Difference	-284	-20	-279	15	-98	11	-116	7	-29	0	-8	-21	-48	-11	-21	-16
	Quinn / Washington Blvd (West Side Access)															
Manual Count	2450	--	--	2450	66	--	--	66	275	185	30	60	89	64	--	25
Simulation	1925	--	--	1925	56	--	--	56	284	203	30	51	86	56	--	30
Difference	-525	--	--	-525	-10	--	--	-10	9	18	0	-9	-3	-8	--	5
	Washington Blvd (East Side Access)															
Manual Count	347	--	--	347	285	--	--	285	630	--	--	630	405	--	--	405
Simulation	243	--	--	243	275	--	--	275	583	--	--	583	460	--	--	460
Difference	-104	--	--	-104	-10	--	--	-10	-47	--	--	-47	55	--	--	55
	Joyce															
Manual Count	1215	10	862	343	822	190	499	133	152	80	50	22	664	246	65	353
Simulation	1113	23	756	334	816	191	483	142	142	79	44	19	656	243	63	350
Difference	-102	13	-106	-9	-6	1	-16	9	-10	-1	-6	-3	-8	-3	-2	-3

Table 3.6: Comparison of Total Observed and Simulated Flows for Midday Period

	Columbia Pike Eastbound				Columbia Pike Westbound				Cross-Street Southbound				Cross-Street Nortbound			
	Total	L	T	R	Total	L	T	R	Total	L	T	R	Total	L	T	R
	Carling Springs															
Manual Count	1749	427	1231	91	1614	141	1210	263	1307	356	453	498	751	114	447	190
Simulation	1740	429	1220	91	1622	159	1199	264	1297	352	450	495	747	117	446	184
Difference	-9	2	-11	0	8	18	-11	1	-10	-4	-3	-3	-4	3	-1	-6
	Four Mile Run															
Manual Count	294	--	--	294	64	64	--	--	--	--	--	--	397	307	--	90
Simulation	278	--	--	278	37	37	--	--	--	--	--	--	390	315	--	75
Difference	-16	--	--	-16	-27	-27	--	--	--	--	--	--	-7	8	--	-15
	Buchanan															
Manual Count	1854	94	1664	96	2958	44	1570	92	378	81	25	139	288	88	26	40
Simulation	1389	131	1139	119	2445	51	1192	96	338	40	28	107	269	72	26	14
Difference	-465	37	-525	23	-513	7	-378	4	-40	-41	3	-32	-19	-16	0	-26
	George Mason															
Manual Count	1661	357	1230	74	1544	184	1196	164	1190	218	705	267	1100	53	820	227
Simulation	1432	338	1036	58	1365	254	889	222	1037	197	723	117	1005	23	786	196
Difference	-229	-19	-194	-16	-179	70	-307	58	-153	-21	18	-150	-95	-30	-34	-31
	Glebe															
Manual Count	1587	--	1412	175	1806	127	1390	289	1598	--	1375	223	1730	--	1552	178
Simulation	1466	--	1279	187	1739	124	1330	285	1550	--	1342	208	1565	--	1430	135
Difference	-121	--	-133	12	-67	-3	-60	-4	-48	--	-33	-15	-165	--	-122	-43
	Walter Reed															
Manual Count	1590	159	1307	124	1830	201	1497	132	833	160	437	236	902	179	449	274
Simulation	1573	154	1300	119	1652	194	1330	128	780	159	425	196	852	138	455	259
Difference	-17	-5	-7	-5	-178	-7	-167	-4	-53	-1	-12	-40	-50	-41	6	-15
	Quinn / Washington Blvd (West Side Access)															
Manual Count	976	--	--	976	122	--	--	122	361	190	15	156	42	32	--	10
Simulation	968	--	--	968	121	--	--	121	364	194	14	156	35	28	--	7
Difference	-8	--	--	-8	-1	--	--	-1	3	4	-1	0	-7	-4	--	-3
	Washington Blvd (East Side Access)															
Manual Count	144	--	--	144	376	--	--	376	723	--	--	723	363	--	--	363
Simulation	145	--	--	145	364	--	--	364	726	--	--	726	348	--	--	348
Difference	1	--	--	1	-12	--	--	-12	3	--	--	3	-15	--	--	-15
	Joyce															
Manual Count	587	30	325	232	789	208	418	163	275	156	77	42	712	348	76	288
Simulation	583	16	329	238	788	205	422	161	275	154	77	44	710	348	75	287
Difference	-4	-14	4	6	-1	-3	4	-2	0	-2	0	2	-2	0	-1	-1

Table 3.7: Comparison of Total Observed and Simulated Flows for PM Peak Period

	Columbia Pike Eastbound				Columbia Pike Westbound				Cross-Street Southbound				Cross-Street Nortbound			
	Total	L	T	R	Total	L	T	R	Total	L	T	R	Total	L	T	R
	Carling Springs															
Manual Count	2159	482	1558	119	2682	209	2176	297	2893	635	796	1462	1069	170	583	316
Simulation	2161	483	1554	124	2634	203	2135	296	2114	478	593	1043	1080	173	583	324
Difference	2	1	-4	5	-48	-6	-41	-1	-779	-157	-203	-419	11	3	0	8
	Four Mile Run															
Manual Count	449	--	--	449	121	121	--	--	--	--	--	--	575	477	--	98
Simulation	373	--	--	373	133	133	--	--	--	--	--	--	590	464	--	126
Difference	-76	--	--	-76	12	12	--	--	--	--	--	--	15	-13	--	28
	Buchanan															
Manual Count	2297	114	2011	172	2958	25	2814	119	378	90	70	218	288	176	68	44
Simulation	1890	110	1612	168	2445	44	2317	98	338	77	68	203	269	159	65	40
Difference	-407	-4	-399	-4	-513	19	-497	-21	-40	-13	-2	-15	-19	-17	-3	-4
	George Mason															
Manual Count	1953	384	1482	87	2541	264	2159	118	2410	211	1771	428	1460	61	1164	235
Simulation	1694	352	1265	77	2228	268	1841	119	2221	194	1689	338	1332	47	1080	205
Difference	-259	-32	-217	-10	-313	4	-318	1	-189	-17	-82	-90	-128	-14	-84	-30
	Glebe															
Manual Count	1666	--	1420	246	2441	168	2020	253	2299	--	2113	186	1781	--	1643	138
Simulation	1575	--	1330	245	2305	154	1918	233	2257	--	2077	180	1596	--	1477	119
Difference	-91	--	-90	-1	-136	-14	-102	-20	-42	--	-36	-6	-185	--	-166	-19
	Walter Reed															
Manual Count	1587	154	1292	141	2758	510	2084	164	1620	222	1150	248	1047	133	623	291
Simulation	1610	159	1309	142	2611	539	1899	173	1570	222	1143	205	1027	112	621	294
Difference	23	5	17	1	-147	29	-185	9	-50	0	-7	-43	-20	-21	-2	3
	Quinn / Washington Blvd (West Side Access)															
Manual Count	1116	--	--	1116	115	--	--	115	448	165	23	260	82	72	--	10
Simulation	1087	--	--	1087	126	--	--	126	434	168	21	245	75	63	--	12
Difference	-29	--	--	-29	11	--	--	11	-14	3	-2	-15	-7	-9	--	2
	Washington Blvd (East Side Access)															
Manual Count	180	--	--	180	527	--	--	527	1263	--	--	1263	314	--	--	314
Simulation	149	--	--	149	523	--	--	523	1248	--	--	1248	299	--	--	299
Difference	-31	--	--	-31	-4	--	--	-4	-15	--	--	-15	-15	--	--	-15
	Joyce															
Manual Count	765	12	440	313	1569	473	983	113	342	196	114	32	1180	570	74	536
Simulation	770	7	457	306	1599	474	1015	110	341	196	112	33	1190	588	70	532
Difference	5	-5	17	-7	30	1	32	-3	-1	0	-2	1	10	18	-4	-4

3.4.3 Traffic Signal Operations Modeling

To evaluate the potential benefits of implementing transit signal priority along Columbia Pike, two sets of traffic signal timings based on observed traffic signal operations were developed for use with the INTEGRATION traffic simulation model. The first set models the MONARC fixed signal timing plans that were defined for use at the time of the study in situations in which the SCOOT system would not be operational. The second set models the signal timings that were implemented by the SCOOT system at all the intersections under its control along the corridor on June 13 and 14, 2000.

Table 3.8, Table 3.9, and Table 3.10 provide the details of the fixed timing plans that were coded within INTEGRATION for the AM peak, Midday and PM peak control periods. Since the MONARC timings that were used to generate these sets of signal timings were developed less than a year before the conduction of the study, it is therefore assumed here that they adequately reflect traffic conditions along Columbia Pike at the time of the study. The only major differences between the original MONARC timings and the simulated timings are as follows:

- While 3- to 4-second yellow intervals followed by 0.5- to 2.5-second all-red intervals are typically used along the corridor, it is assumed in the simulation model that all phases are terminated by the display of a 3-second yellow interval. This assumption is made to allow the INTEGRATION model to consider effective signal timings rather than displayed signal indications. Contrary to what is observed in reality, the model does not allow vehicle to cross an intersection after a yellow interval has been displayed. Therefore, in order to adequately simulate existing traffic conditions along the corridor, a portion of the yellow interval had to be treated as a green indication. In this case, no adjustments had to be made for the startup loss time at the beginning of the green interval, as this loss time is automatically taken into consideration by the dynamic nature of the simulation model.
- While phase actuation is used at some intersections, such as for the protected left-turn at the intersection with Joyce, it is assumed in the simulation that there is no

phase actuation at any intersection along the corridor. For intersections featuring phase actuation, signal timings reflecting average or minimum green durations were coded based on the amount of simulated traffic going through the intersection.

- Exact signal timings for the intersections with Jefferson, Monroe and Joyce were not provided by the Department of Public Works of Arlington County. The timings that were coded in INTEGRATION were therefore based on available minimum and maximum green information, as well as on comparisons with other intersections.

Similar to Table 3.8, Table 3.11 lists the signal timings that were developed to simulate observed SCOOT traffic signal control along the study corridor for the AM peak period. Similar tables were also generated for the Midday and PM peak control periods. These timings are based on the following elements:

- The set of signal timings shown in the table does not model signal operations at the intersections with Carlin Spring, Jefferson, Greenbrier, Navy Annex, and Joyce, as these intersections are not controlled by the SCOOT system. For these intersections it is assumed that the fixed signal timings defined in Table 3.8, Table 3.9, and Table 3.10 remain in use in all SCOOT control scenarios.
- Signal timings are defined for a series of consecutive 15-minute intervals. While the Traffic Engineering Division of the Department of Public Works of Arlington County provided detailed, cycle-by-cycle, listings of the signal timings that were implemented by the SCOOT system at all intersections under its control on either June 13 or June 14, 2000, such level of details could not readily be simulated within the current version of INTEGRATION. To account for this difficulty, a series of 15-minute fixed timing plans averaging the implemented SCOOT timings at each intersection on June 13 and 14 were therefore developed for simulation purposes. As it can be observed, while the chosen 15-minute control interval does not allow cycle-to-cycle fluctuations in signal timings to be simulated, it still provide an adequate modeling of the ability of the SCOOT system to alter signal timings in response to changes in traffic demands.

Table 3.8: Modeled Fixed-Time Signal Timings for AM Peak Period

Intersection	Cycle	Offset[1]	Green Split[2]				
			Columbia Pike Main Green ⇆	Cross-street Protected Left ↰ ↳	Cross-street Main Green ⇵	Columbia Pike Protected Left ⬏⬐	Columbia Pike Leading Green → or ←
Carlin Spring	130	0	51	20	31	18	10 (Eastbound)
Jefferson	100	39	66		34		
Greenbrier	100	56	64		26	10	
Dinwiddie	100	84	66		34		
Four Mile Run	100	2	77		23		
Buchanan	100	11	76		24		
Wakefield	100	22	75		25		
Thomas	100	36	73		27		
Taylor	100	32	76		24		
George Mason	100	53	40		39		21 (Eastbound)
Quincy	100	70	75		25		
Monroe	100	4	75		25		
Glebe	100	15	55		45		
Highland	100	15	77		23		
Walter Reed	100	27	56		32		12 (Westbound)
Barton	100	53	73		27		
Wayne	100	65	75		25		
Courthouse	100	75	65		35		
Quinn	100	8	75		25		
Navy Annex	100	75	72		28		
Joyce	100	0	57		33	10	

[1] Offset referenced to Columbia Pike Main Green at Carlin Spring

[2] Green splits includes a 3-second yellow interval terminating the green interval

Table 3.9: Modeled Fixed-Time Signal Timings for Midday Period

Intersection	Cycle	Offset 1	Green Split 2				
			Columbia Pike Main Green ⇆	Cross-street Protected Left ↰↳	Cross-street Main Green ⇵	Columbia Pike Protected Left ⬏⬐	Columbia Pike Leading Green → or ←
Carlin Spring	75	0	34	11	20	10	
Jefferson	75	72	44		29		
Greenbrier	75	5	38		27	10	
Dinwiddie	75	44	43		32		
Four Mile Run	75	32	52		23		
Buchanan	75	32	52		23		
Wakefield	75	5	51		24		
Thomas	75	70	48		27		
Taylor	75	67	51		24		
George Mason	75	48	35		29		11 (Eastbound)
Quincy	75	25	50		25		
Monroe	75	0	50		25		
Glebe	75	64	38		37		
Highland	75	12	52		23		
Walter Reed	75	22	34		28		13 (Westbound)
Barton	75	56	47		28		
Wayne	75	59	49		26		
Courthouse	75	62	41		34		
Quinn	75	20	51		24		
Navy Annex	75	52	47		28		
Joyce	75	0	36		29	10	

[1] Offset referenced to Columbia Pike Main Green at Carlin Spring

[2] Green splits includes a 3-second yellow interval terminating the green interval

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Table 3.10: Modeled Fixed-Time Signal Timings for PM Peak Period

Intersection	Cycle	Offset [1]	Green Split [2]					
			Columbia Pike Main Green ⇆	Cross-street Protected Left ↰↳	Cross-street Leading Green ↰↳	Cross-street Main Green ⇂↾	Columbia Pike Protected Left ⬏⬐	Columbia Pike Leading Green → or ←
Carlin Spring	140	0	46	20	20	31	17	15 (Westbound)
Jefferson	105	39	71			34		
Greenbrier	105	97	67			27	11	
Dinwiddie	105	61	72			33		
Four Mile Run	105	47	67			38		
Buchanan	105	39	78			27		
Wakefield	105	25	80			25		
Thomas	105	8	78			27		
Taylor	105	0	80			25		
George Mason	105	88	57			38		10 (Eastbound)
Quincy	105	70	80			25		
Monroe	105	38	80			25		
Glebe	105	29	60			45		
Highland	105	15	74			31		
Walter Reed	105	5	52			35		18 (Westbound)
Barton	105	90	79			26		
Wayne	105	76	79			26		
Courthouse	105	62	71			34		
Quinn	105	16	81			24		
Navy Annex	105	88	77			28		
Joyce	105	0	62			33	10	

[1] Offset referenced to Columbia Pike Main Green at Carlin Spring

[2] Green splits includes a 3-second yellow interval terminating the green interval

Table 3.11: Modeled SCOOT Signal Timings for AM Peak Period

Intersection	Period	Cycle	Offset [1]	Green Split [2]		
				Columbia Pike Main Green ⇆	Cross-street Main Green ⇅	Columbia Pike Leading Green → or ←
Dinwiddie	7:00-7:15	92	84	51	41	
	7:15-7:30	104	84	58	46	
	7:30-7:45	105	84	60	45	
	7:45-8:00	105	84	62	43	
	8:00-8:15	105	84	58	47	
	8:15-8:30	105	84	62	43	
	8:30-8:45	105	84	63	42	
	8:45-9:00	104	84	62	42	
Four Mile Run	7:00-7:15	92	10	65	27	
	7:15-7:30	104	102	76	28	
	7:30-7:45	105	102	75	30	
	7:45-8:00	105	102	70	35	
	8:00-8:15	105	102	76	29	
	8:15-8:30	105	102	75	30	
	8:30-8:45	105	102	75	30	
	8:45-9:00	104	102	75	29	
Buchanan	7:00-7:15	92	19	61	31	
	7:15-7:30	104	7	72	32	
	7:30-7:45	105	6	73	32	
	7:45-8:00	105	6	75	30	
	8:00-8:15	105	6	73	32	
	8:15-8:30	105	6	75	30	
	8:30-8:45	105	6	76	29	
	8:45-9:00	104	7	74	30	
Wakefield	7:00-7:15	92	30	70	22	
	7:15-7:30	104	18	80	24	
	7:30-7:45	105	17	77	28	
	7:45-8:00	105	17	80	25	
	8:00-8:15	105	17	73	32	
	8:15-8:30	105	17	80	25	
	8:30-8:45	105	17	80	25	
	8:45-9:00	104	18	76	28	
Thomas	7:00-7:15	92	44	78	14	
	7:15-7:30	104	32	79	25	
	7:30-7:45	105	31	80	25	
	7:45-8:00	105	31	74	31	
	8:00-8:15	105	31	84	21	
	8:15-8:30	105	31	77	28	
	8:30-8:45	105	31	80	25	
	8:45-9:00	104	32	87	17	
Taylor	7:00-7:15	92	40	67	25	
	7:15-7:30	104	28	79	25	
	7:30-7:45	105	27	80	25	
	7:45-8:00	105	27	81	24	
	8:00-8:15	105	27	80	25	
	8:15-8:30	105	27	79	26	
	8:30-8:45	105	27	80	25	
	8:45-9:00	104	28	79	25	
George Mason	7:00-7:15	92	61	26	56	10 (Eastbound)
	7:15-7:30	104	49	30	62	12
	7:30-7:45	105	48	27	66	12
	7:45-8:00	105	48	28	64	13
	8:00-8:15	105	48	27	66	12
	8:15-8:30	105	48	29	64	12
	8:30-8:45	105	48	31	63	11
	8:45-9:00	104	49	29	64	11
Quincy	7:00-7:15	92	78	64	28	
	7:15-7:30	104	66	72	32	
	7:30-7:45	105	65	72	33	
	7:45-8:00	105	65	75	30	
	8:00-8:15	105	65	73	32	
	8:15-8:30	105	65	73	32	
	8:30-8:45	105	65	75	30	
	8:45-9:00	104	66	73	31	

Table 3.11: Modeled SCOOT Signal Timings for AM Peak Period (cont'd)

Intersection	Period	Cycle	Offset [1]	Green Split [2]		
				Columbia Pike Main Green ⇆	Cross-street Main Green ⇅	Columbia Pike Leading Green → or ←
Monroe	7:00-7:15	92	20	64	28	
	7:15-7:30	104	100	74	30	
	7:30-7:45	105	99	73	32	
	7:45-8:00	105	99	70	35	
	8:00-8:15	105	99	72	33	
	8:15-8:30	105	99	70	35	
	8:30-8:45	105	99	72	33	
	8:45-9:00	104	100	71	33	
Glebe	7:00-7:15	92	31	36	56	
	7:15-7:30	104	7	44	60	
	7:30-7:45	105	5	40	65	
	7:45-8:00	105	5	41	64	
	8:00-8:15	105	5	42	63	
	8:15-8:30	105	5	46	59	
	8:30-8:45	105	5	46	59	
	8:45-9:00	104	7	43	61	
Highland	7:00-7:15	92	31	73	19	
	7:15-7:30	104	7	79	25	
	7:30-7:45	105	5	79	26	
	7:45-8:00	105	5	79	26	
	8:00-8:15	105	5	79	26	
	8:15-8:30	105	5	79	26	
	8:30-8:45	105	5	79	26	
	8:45-9:00	104	7	79	25	
Walter Reed	7:00-7:15	92	43	52	31	9 (Westbound)
	7:15-7:30	104	19	50	41	13
	7:30-7:45	105	17	49	41	15
	7:45-8:00	105	17	52	41	12
	8:00-8:15	105	17	47	42	16
	8:15-8:30	105	17	49	43	13
	8:30-8:45	105	17	51	41	13
	8:45-9:00	104	19	49	43	12
Barton	7:00-7:15	92	69	64	28	
	7:15-7:30	104	45	74	30	
	7:30-7:45	105	43	73	32	
	7:45-8:00	105	43	70	35	
	8:00-8:15	105	43	72	33	
	8:15-8:30	105	43	70	35	
	8:30-8:45	105	43	72	33	
	8:45-9:00	104	45	71	33	
Wayne	7:00-7:15	92	81	65	27	
	7:15-7:30	104	57	76	28	
	7:30-7:45	105	55	71	34	
	7:45-8:00	105	55	76	29	
	8:00-8:15	105	55	79	26	
	8:15-8:30	105	55	72	33	
	8:30-8:45	105	55	73	32	
	8:45-9:00	104	57	68	36	
Courthouse	7:00-7:15	92	91	56	36	
	7:15-7:30	104	67	68	36	
	7:30-7:45	105	65	62	43	
	7:45-8:00	105	65	65	40	
	8:00-8:15	105	65	66	39	
	8:15-8:30	105	65	64	41	
	8:30-8:45	105	65	65	40	
	8:45-9:00	104	67	67	37	
Quinn	7:00-7:15	92	32	69	23	
	7:15-7:30	104	100	77	27	
	7:30-7:45	105	98	78	27	
	7:45-8:00	105	98	74	31	
	8:00-8:15	105	98	76	29	
	8:15-8:30	105	98	78	27	
	8:30-8:45	105	98	79	26	
	8:45-9:00	104	100	77	27	

[1] Offset referenced to Columbia Pike Main Green at Carlin Spring

[2] Green splits includes a 3-second yellow interval terminating the green interval

- Within any given control interval, all intersections along the corridor are assumed to be operated with an identical cycle time to ensure signal coordination and traffic progression. This common cycle time was determined by selecting within each control interval the most representative observed cycle across all SCOOT-controlled intersections. Within each interval, with the exception of the first interval covering the period from 8:00 to 8:15 AM, typical observed cycle times varied between 104 and 106 seconds, with a few intersections having cycles in some 15-minute intervals as low as 102 seconds and as high as 108 seconds. In this case, it can particularly be observed the selected common cycle for each interval within the AM peak period are generally fairly close to the corresponding MONARC fixed-time cycle of 100 seconds.

Alternatively to the simulation of fixed-time and average observed SCOOT signal timings, the traffic signal optimization routines embedded in the INTEGRATION model were also used to emulate SCOOT-like adaptive signal control along the study corridor. These optimization routines, which are described in greater details in Section 6.3, were developed with the intent to replicate the SCOOT traffic signal optimization logic within the INTEGRATION model. Similar to SCOOT, these optimization routines allow the phase split, cycle time and offset of each intersection to be adjusted to recently observed traffic conditions within the simulation at user-defined intervals. However, contrary to SCOOT, there is no constraints on the maximum amount of change in cycle time, green split and signal offset that can be implemented at the end of each optimization step. Another difference is that the INTEGRATION signal control logic was not set to consider pedestrian clearance intervals at individual intersections, thus allowing for the implementation of shorter phases than what would be observed in reality with the SCOOT system.

3.4.4 Traffic Signal Operations Modeling

To model bus stops, two approaches were taken. First, the location of curbside stops along given links could be directly specified in the input files to the simulation model.

Second, for stops with a bus bay, links were added to the coded network to allow the buses to move out of the way of the general traffic when stopping to load and unload passengers. Since buses along Columbia Pike typically wait for platoons of vehicles to finish passing before resuming their course, the exit of a bus from the last link modeling a bus bay was simulated using a yield sign. This effectively forced buses to wait for an appropriate gap between successive vehicles before reinserting themselves into the traffic stream, as observed in reality.

Transit dwell times at individual bus stops along the corridor were modeled based on the information shown in Table 3.1. For the Midday and PM peak periods, the average observed dwell times and coefficient of variation of each section of the corridor were assigned to the corresponding bus stops. For the sections with no observations, the corridor averages for the corresponding period were used instead. For the AM peak period, for which there is little information about bus dwell times, the section averages for the PM peak period were used to characterize transit operations at the various bus stops along the corridor, expect for those located within sections for which dwell time observations were made. For the cross-street stops, for which no observations are available, bus dwell times were further specified according to the corridor average for each period. Finally, since INTEGRATION does not currently allow the modeling of buses bypassing a stop when there are no passengers to load or unload, it was assumed that all buses needed to stop at all the stops located along their specific route.

To fully evaluate the potential benefits of alternative transit priority schemes and correctly simulate transit activities at various bus stops, four different types of vehicles were explicitly modeled within INTEGRATION. The first type of vehicles includes all passenger cars. The second type includes regular buses traveling primarily along Columbia Pike, explicitly, buses traveling along routes 16A, 16B, 16C, 16D, 16E, 16G, 16J, 16U, 16W, 16X, 24M, and 24P. Vehicles of the third type include all buses traveling primarily on streets crossing Columbia Pike, namely buses traveling on all routes 10, 22, 25 and 28. Finally, the fourth type of vehicles models express buses traveling along Columbia Pike, in this case buses traveling exclusively along route 16F.

Following this classification, transit operations at the various bus stops could then be correctly modeled by simply indicating which vehicle types service a particular bus stop. Various transit priority schemes could also be developed, by simply adding or removing vehicle types from the list of vehicles having priority of passage at each intersection.

Figure 3.18 further illustrates the demand for each type of transit vehicles for the AM peak, Midday and PM peak periods that was determined based on published transit schedules. The figure indicates that a total of 96, 46 and 100 buses are simulated for the AM peak, Midday and PM peak period, respectively. In particular, it is observed that there are no express buses running during the Midday period and that these vehicles also constitute a small fraction of the overall bus flow in the other periods. Specifically, only 8 and 11 express buses are simulated for the AM and PM peak periods. Based on the information shown in the figure, it is therefore expected that providing priority to either the regular or cross-street buses will have a much greater impact on the system's performance than scenarios considering providing priority only to the express buses.

Finally, buses occupancies were not explicitly modeled for this study. Such a modeling was not necessary as the INTEGRATION model provides detailed simulation results for each type of simulated vehicles. This allowed simulation results reflecting various vehicle occupancies to be obtained by appropriately weighting the performance measures of each type of vehicle.

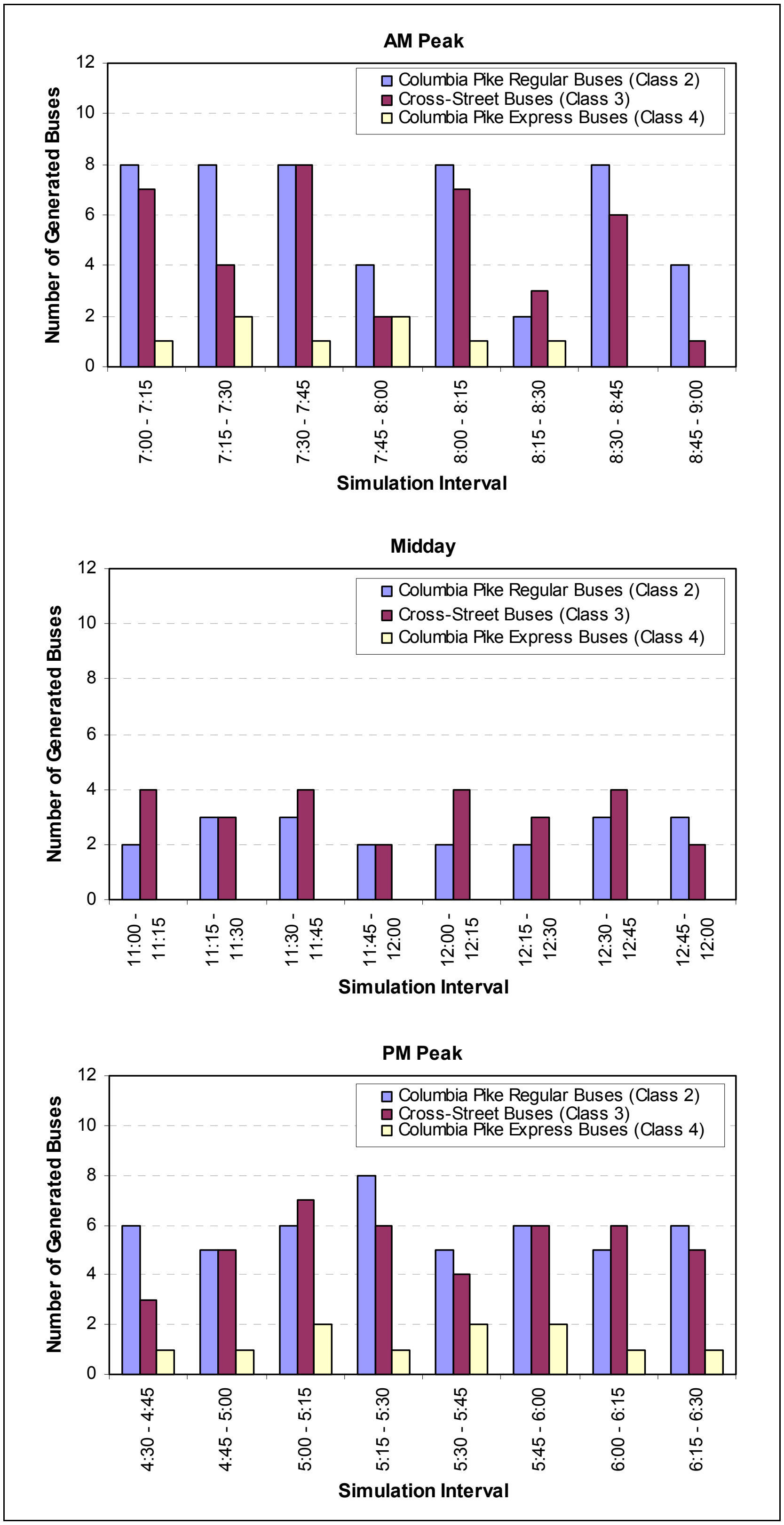


Figure 3.18: Simulated Bus Demands for the AM Peak, Midday and PM Peak Periods

3.5 Traffic Signal Control Logic

This section provides general technical information about the various signal control logic that are being considered in the simulation study. Specifically, the section provides information about the logic that is used by the INTEGRATION simulation model to provide priority to approaching transit vehicles, the logic used by the SCOOT system to adjust the signal timings to observed traffic conditions, and the logic used by the INTEGRATION model to emulate SCOOT control with unrestricted signal change capabilities at individual signalized intersections.

3.5.1 Prioritized Transit Traffic Signal Control

The transit priority logic that is embedded in the INTEGRATION 2.30c model is relatively simple. Specifically, vehicles are detected when they are within 100 m of the traffic signal. The logic then provides either a green extension or an early green recall to accommodate the approaching transit vehicle, subject to the need to maintain the cycle length.

The logic of Figure 3.19 is used within INTEGRATION to determine whether signal changes are required at an intersection to accommodate an approaching transit vehicle. The operation of this logic is best described through an example. In Figure 3.20, if it is assumed that the traffic signals A and B operate on a two-phase mode with a common cycle length, the detection of a transit vehicle traveling eastbound while traffic on the east/west travel direction is being served may results in a number of possible outcomes depending on when the detected transit vehicle is projected to arrive at intersection A within the signal cycle:

- If the transit vehicle is projected to arrive early in the green interval so that it can proceed uninterrupted through the intersection, no alterations are made to the signal timings.
- Alternatively, if the transit vehicle is projected to arrive after the end of the green interval, the interval is extended at increments of 5 seconds until the transit

vehicle is served or the maximum green interval duration has been reached. Currently the maximum green time is set to equal the cycle length, minus the summation of the intergreen times of all the phases defined in the signal cycle and the summation of a 5-second minimum green for each phase defined within the signal cycle. It should be noted that the transit priority logic is checked each second to identify what changes if any should be made to the signal timings.

- If, on the other hand, the traffic signal at intersection A serves the north/south approaches as the transit vehicle arrives, the priority logic truncates the north/south phase after providing the required amber interval.
- Finally, if transit vehicles are detected on two conflicting approaches, as illustrated in Figure 3.21, the transit signal priority logic makes no changes to the signal timings as the priority calls from any approach are equally weighed.

Enhancements to the INTEGRATION transit priority logic are being incorporated in order to provide priority that is weighed by the occupancy of the transit vehicles. Further enhancements to the logic will include the capability of altering the distance upstream the traffic signal where the bus is detected, the minimum green time, the maximum green time, and the green extension parameters. Finally, the enhanced logic will also consider the level of congestion on conflicting approaches in such way that priority would only be provided to approaching transit vehicles when traffic conditions around a signalized intersection permit signal alterations to be implemented without generating undue congestion.

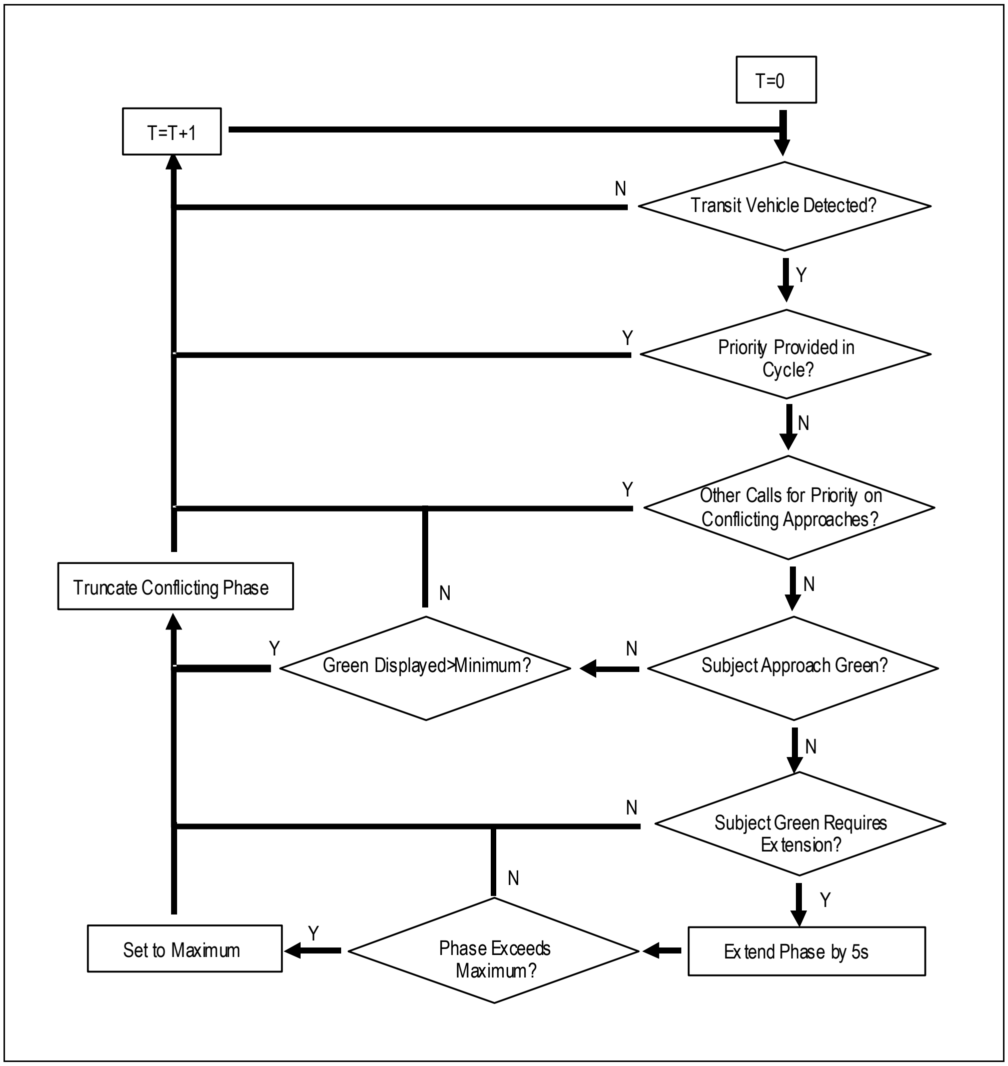


Figure 3.19: Flow Chart of INTEGRATION Transit Priority Logic

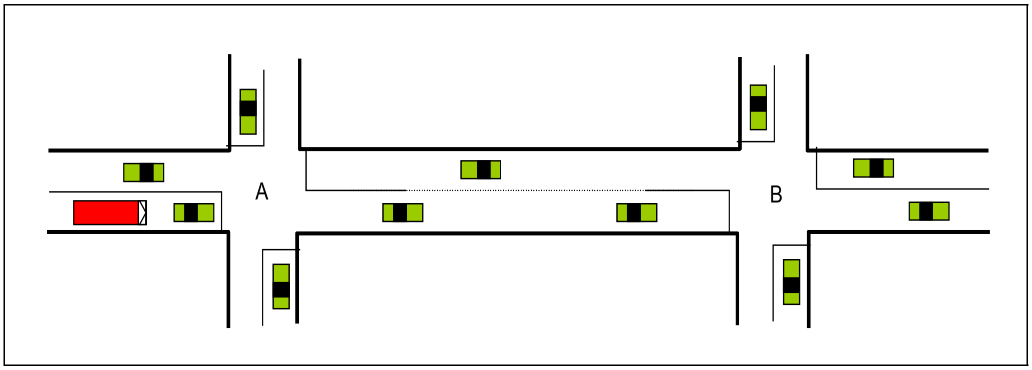


Figure 3.20: Example Illustration of Transit Signal Priority with call from Eastbound Approach

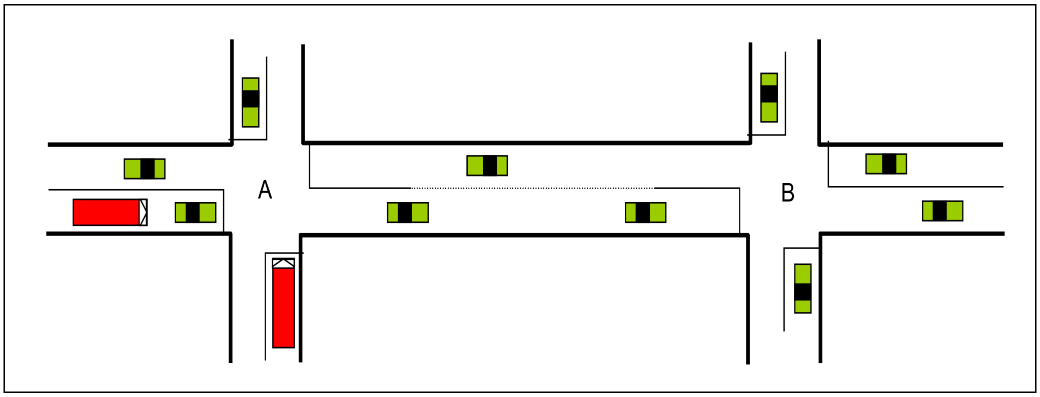


Figure 3.21: Example of Transit Signal Priority with calls from Eastbound and Northbound Approaches

3.5.2 SCOOT Adaptive Traffic Signal Control

The main philosophy of the SCOOT traffic signal control system is to react to changes in observed average traffic demands by making frequent, but small, adjustments to the signal cycle time, green allocation, and offset of every controlled intersection. For each coordinated area, the system evaluates every 5 minutes, or 2.5 minutes if appropriate, whether the common cycle time in operation at all intersections within the area should be changed to keep the degree of saturation of the most heavily loaded intersection at or below 90%. To maintain some stability in the operations of coordinated networks, changes in cycle time are limited to a maximum of 8 seconds per optimization. A few seconds before each scheduled phase change, the signal optimizer also evaluates if the current phase should be terminated earlier, as scheduled, or later. In this case, the optimizer implements at each intersection the alteration that will minimize the estimated degree of saturation on any approach to the intersection. In order to avoid large transition disturbances, changes in the green allocation are again limited to 8 seconds at each intersection. Finally, once during each signal cycle, the optimizer further assesses whether the offset of each intersection should be modified to reduce stops and delay on the intersection approaches. Once more, these changes are limited to a maximum of 8 seconds to ensure stability of operations.

In order to determine the appropriate signal changes to implement, the SCOOT system continuously monitors the traffic demand placed on each controlled intersection. Traffic demand is monitored using presence detectors installed upstream or midstream on each significant approach to an intersection, as shown in Figure 3.22. These detectors are typically located at the exit of the upstream intersection to allow the system to obtain the most direct advance information about future arrivals at the intersection being controlled. These detectors also allow the system to know whether a queue of vehicles has grown to such extent as to threaten to spill across the upstream intersection.

In typical installations, the traffic detectors are polled four times per second. Based on the collected information, updated average cyclic flow profiles are then generated every few seconds and stored in a central computer for use in the next traffic signal optimization. As illustrated in Figure 3.22, cyclic flow profiles can be though of as histograms giving the average number of vehicles that were observed to arrive at an intersection on a given approach during each of the intervals dividing the current signal cycle. These profiles are generated within SCOOT by combining the most recent traffic flow data with historical observations using a moving average process. This is done primarily to ensure the stability of operations of the systems. While the SCOOT system is adaptive in nature, it was primarily designed to react to long-term, slow variations in traffic demand, and not to short-term random fluctuations. As a result of this design choice, the flow profiles generated by the system do not represent actual traffic conditions, but characterize instead recent average traffic conditions.

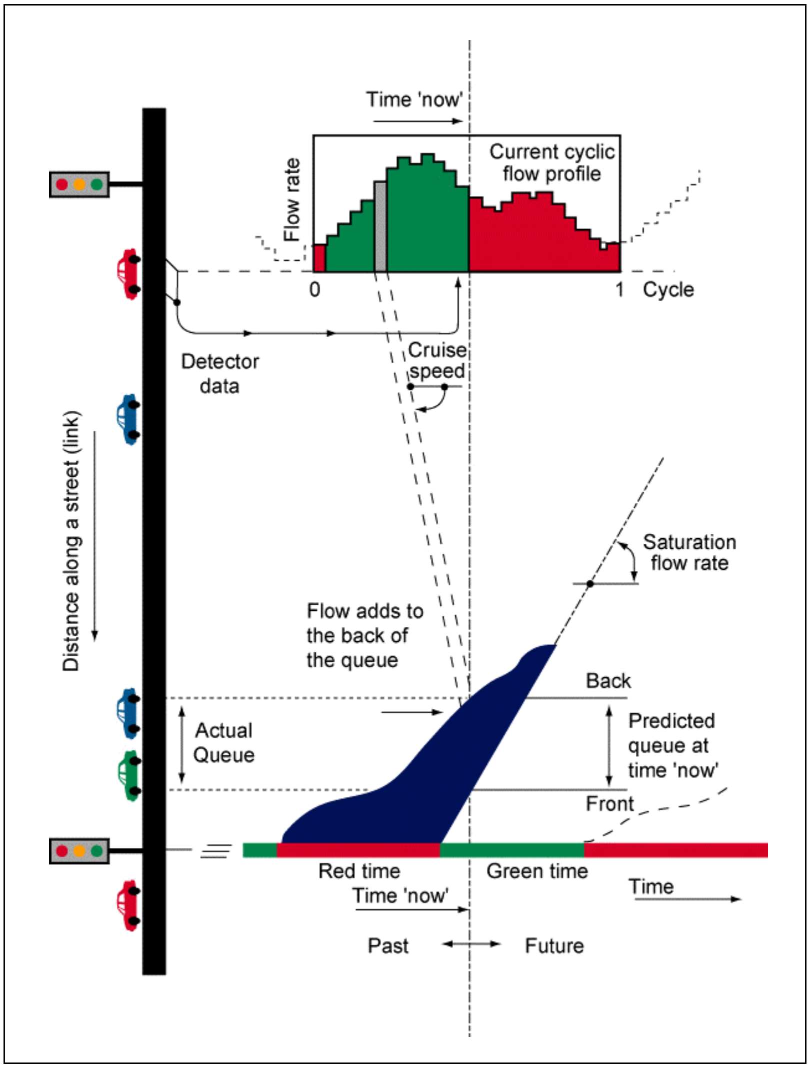


Figure 3.22: SCOOT Control Philosophy

(Transportation Research Laboratory Limited, 1999)

3.5.3 INTEGRATION Traffic Signal Control

The signal optimization routines that are embedded in the INTEGRATION simulation model were developed to provide traffic signal control logic similar to the control philosophy of the SCOOT model. These routines allow the INTEGRATION model to adjust at regular intervals the cycle time, green split and signal offset of individual intersections so that they better match observed traffic demands within a simulation. In this case, the INTEGRATION model allows the cycle time and green split of individual intersections to be adjusted at intervals defined by the model's user. The signal offset, however, is always adjusted at the end of each signal cycle.

Within the model, the cycle time and green split of individual intersections are determined using the optimization technique described in the Canadian Capacity Guide for Signalized Intersections (ITE, 1995). This technique is similar to the Webster-Cobbe signal optimization method that is generally used by traffic engineers to determine the timings of individual intersections. This method determines the green split and cycle time of signalized intersections by analyzing on a lane-by-lane basis the arrival and departure flows on each intersection approach.

The signal optimization method that is followed by INTEGRATION initiates the determination of optimal set of signal timings by first using Equations 1 to 3 to determine the optimal cycle time to use at the intersection being considered. In this case, contrary to SCOOT, which allows the cycle time of a critical intersection within a group of intersections to be used as the common cycle time for all the intersections within the group, the INTEGRATION model only considers signalized intersection on an individual basis.

$$y_i = \frac{q_i}{S_i} \tag{1}$$

$$Y = \sum_j y_{ij} = \sum_j \frac{q_{ij}}{S_{ij}} \tag{2}$$

$$C_{opt} = \frac{1.5L + 5}{1 - Y} \tag{3}$$

where:

y_i = Flow ratio for lane i,
y_{ij} = Flow ratio for critical lane i and phase j,
Y = Intersection flow ratio,
q_i = Arrival flow in lane i (passenger car units/hour),
q_{ij} = Arrival flow of critical lane i in phase j (passenger car units/hour),
S_i = Saturation flow for lane i (passenger car units/hour),
S_{ij} = Saturation flow of critical lane i in phase j (passenger car units/hour),
L = Intersection total lost time (seconds),
C_{opt} = Optimal cycle time (seconds).

Once the intersection's optimal cycle is known, the INTEGRATION model then uses Equation 4 and 5 to apportion the total available green time between the various phases serving traffic at the intersection being considered in proportion to the flow ratio *y* of each phase.

$$\sum g_j = C_{opt} - \sum_j I_j \qquad [4]$$

$$g_j = \sum g_j \cdot \frac{y_j}{Y} \qquad [5]$$

where:

g_j = Green interval for phase j (seconds),
I_j = Intergreen period following phase j (seconds).

Finally, the ideal signal offset for each intersection is determined in a last step by minimizing a performance index function that is a combination of stops and delay. This minimization is done using a cyclic flow profile approach similar to the one used in TRANSYT-7F and SCOOT.

3.6 Simulation Runs

To evaluate the benefits of implementing transit priority and adaptive signal control along Columbia Pike, two sets of simulations were conducted. The first set evaluated the impacts of transit priority and adaptive signal control during the AM peak period, when traffic demand is high and highly directional. The second set evaluated the impacts of transit priority and adaptive signal control during the Midday traffic period, when the demand is lower and does not exhibit any clear directional pattern. No simulation were conducted for the PM peak period, as it was assumed that the similarity of traffic conditions between the AM and PM peak periods, with the exception of a reversed directional flow pattern, would produce similar results.

For both the AM peak and Midday periods, evaluations of alternative transit priority and adaptive control schemes were conducted by simulating traffic conditions over a 2.5-hour period. This 2.5-hour period comprises the nominal two-hour duration of each control period, that is, the interval extending from 7:00 to 9:00 AM for the AM peak period and from 11:00 AM to 1:00 PM for the Midday period, but adds to its two 15-minute intervals, one at the start of the simulation and one at the end. The purpose of the leading 15-minute interval is to load the simulated network with an initial set of vehicles so that the evaluation will not start with an empty network. This loading is done by simulated the same traffic demand as the one that was modeled for the first 15-minute interval of the nominal two-hour control period, i.e., the demand between 7:00 and 7:15 for the AM period and between 11:00 and 11:15 for the Midday period. On the other hand, the purpose of the terminal 15-minute interval is to clear the network before compiling the performance measures so that comparisons between scenarios can be made using the same number of simulated vehicles. This is done by assuming that no new vehicle is entering the network during the interval.

For each combination of signal control and transit priority scenarios, a total of six simulation runs were made using different random seed number. These runs were made to account for the stochastic nature of the INTEGRATION model. Therefore, unless otherwise noted, the results reported in the remainder of this report express the performance measures that were obtained by averaging the results from six individual runs and not the results from individual runs.

4 ANALYSIS RESULTS FROM COLUMBIA PIKE STUDY

4.1 AM Peak Analysis Results

This section provides an analysis of the results of the simulations that were conducted to determine the potential benefits of implementing transit priority along Columbia Pike during the AM peak period (7:00 a.m. to 9:00 a.m.). Since adaptive signal control strategies are considered in the simulation study, the section first provides an analysis of the impacts of these control strategies on traffic performance along the corridor before following with detailed evaluations of the potential benefits that can be obtained under various signal control strategies from providing priority to transit vehicles.

4.1.1 Impact of adaptive signal control on Corridor

Figure 4.1 and Figure 4.2 compare the green split and cycle time that were determined for the intersections of George Mason and Glebe under the various signal control scenarios considered. For the fixed-time and SCOOT scenarios, the figures illustrate the timings listed in Table 3.8 and Table 3.11. For the INTEGRATION scenarios, the figures illustrate the timings that were determined every 5 minutes by the model's signal optimization routines based on observed simulated traffic and under the assumption that no transit vehicle would obtain priority of passage at signalized intersections. Figure 4.3 and Figure 4.4 complete the presentation of the results by illustrating the impacts that the various signal control strategies considered have on simulated traffic performance. Specifically, Figure 4.3 compares the changes in vehicle travel time, delay, stops, fuel consumption and emissions that result from replacing the fixed signal timings of Scenario 1 by each of the alternative adaptive signal control strategies defined in Scenarios 2 to 5, while Figure 4.4 compares the individual approach delays for each signal control strategy.

In Figure 4.1 and Figure 4.2, it is first observed that all signal control strategies result in relative relatively similar cycle times, with the three following exceptions:

- While the cycle time at both intersections typically remains around 100 seconds in most scenarios, the scenario in which the INTEGRATION model determines the green split, signal offset and cycle time result in the use of a 130-second cycle. Such a long cycle time was not expected as the intersections at both the western end (Jefferson and Greenbrier) and eastern end (Navy Annex and Joyce) of the corridor are assumed to remain operated with a fixed 100-second cycle throughout the simulation period. Therefore, since platoons of vehicles were sent towards the middle section of the corridor at intervals of 100 seconds, it was hypothesized that the cycle time determined by INTEGRATION model at each intersection would be around 100 second in this case.
- For the scenario in which the INTEGRATION model determines only the green split and signal cycle time, the simulated cycle times vary between 45 and 65 seconds. Again, a 100-second cycle was expected for this scenario. One element of particular interest here is the fact the cycle times determined by the INTEGRATION signal optimization routines are about one half the fixed cycle times used at the intersections at both ends of the corridor. While the INTEGRATION model optimizes signalized intersections individually and is therefore not bound to maintain a common cycle at all intersections along the corridor, the use of cycle times varying between 45 and 65 seconds could be an indication that the model attempted to "double cycle" the operations of these intersections so as to reduce the delays experienced by drivers while maintaining some coordination with the fixed-time controlled intersections at both ends of the corridor. This signal control technique offers the advantage of reducing delays, but usually at the expense of increased vehicle stops. These impacts are confirmed in the diagrams of Figure 4.3, which indicate that the INTEGRATION Split-Cycle strategy reduced delays for the general traffic by 10% when compared to fixed-time control, but at the expense of an increase in vehicle stops of about 6%.
- The final observation concerns the variance of green splits from one scenario to another. For the intersection with George Mason, Figure 4.1 indicates a

significant variability of green splits between the various signal control scenarios considered. Figure 4.2, on the other hand, indicates for the intersection with

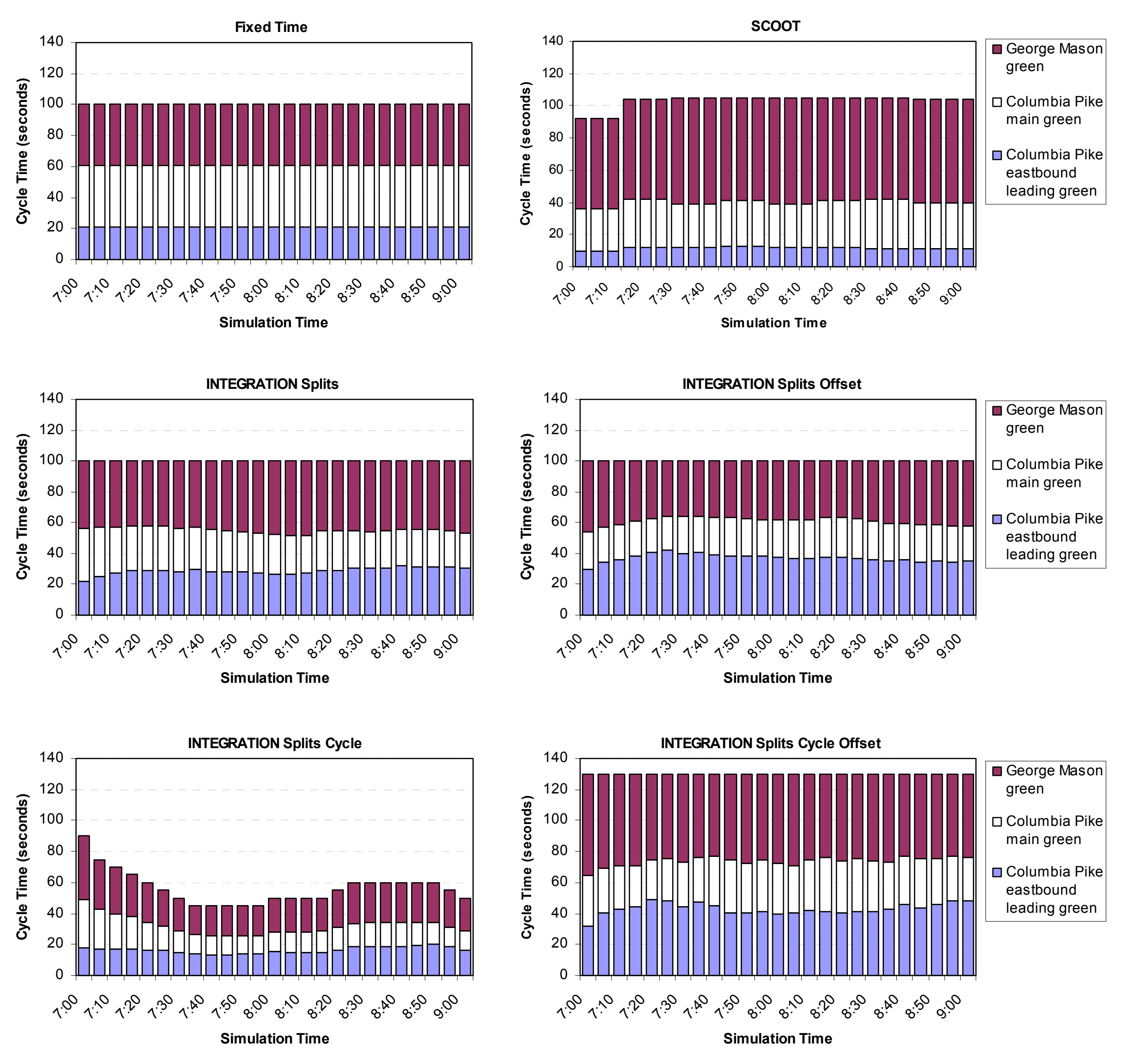


Figure 4.1: Simulated AM Peak Signal Timing Plans at George Mason Intersection

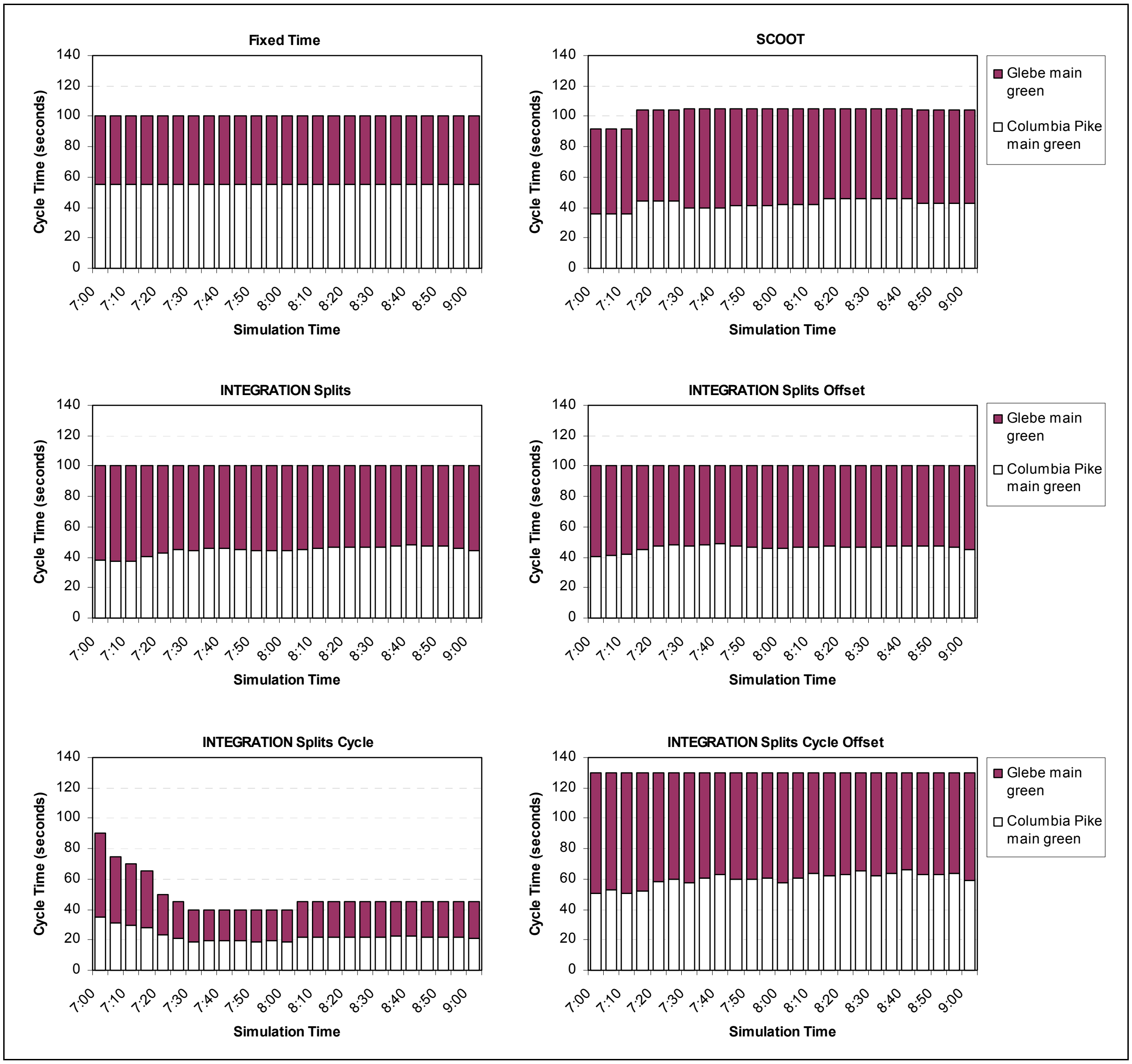
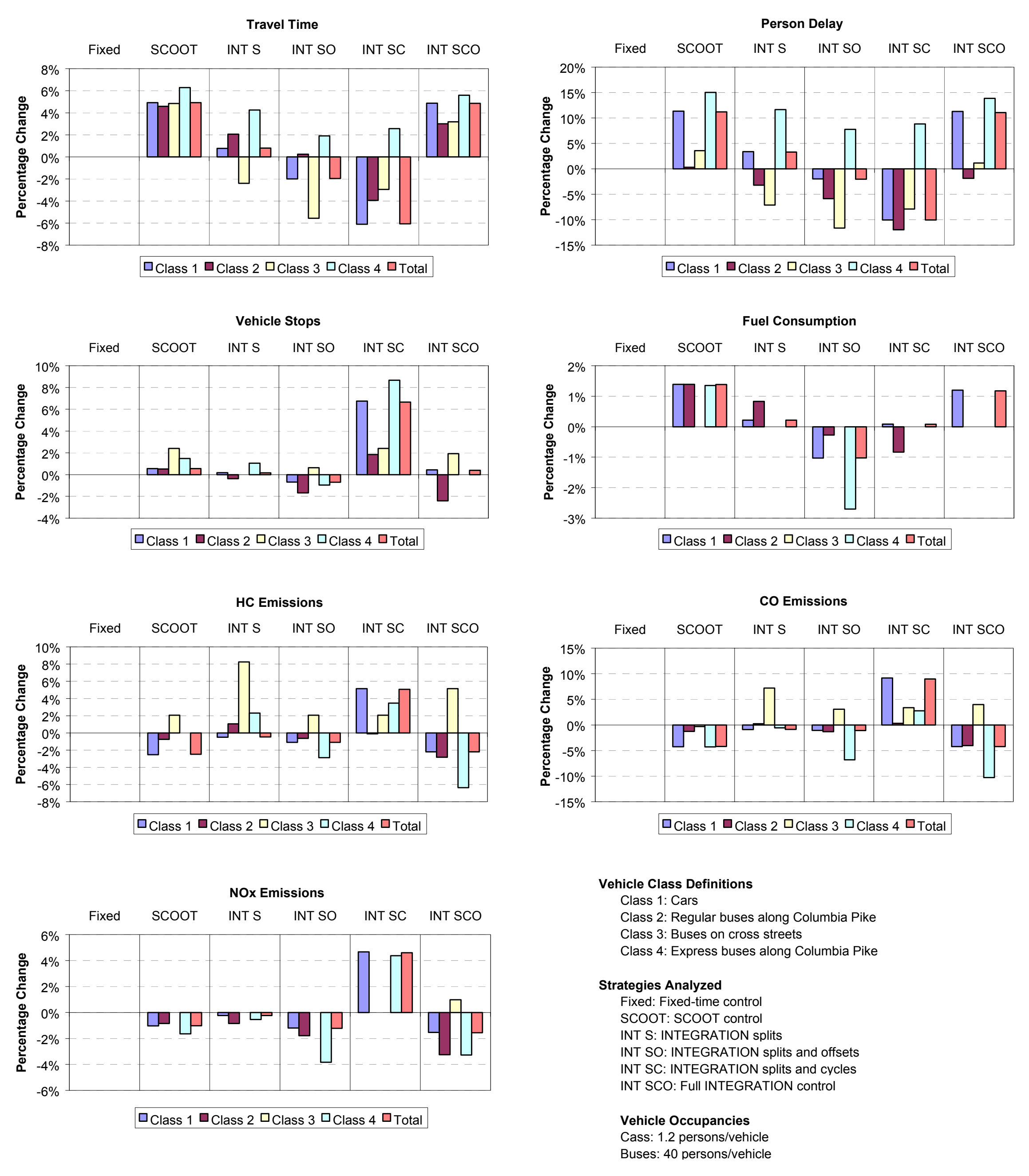


Figure 4.2: Simulated AM Peak Signal Timing Plans at Glebe Intersection



Vehicle Class Definitions
Class 1: Cars
Class 2: Regular buses along Columbia Pike
Class 3: Buses on cross streets
Class 4: Express buses along Columbia Pike

Strategies Analyzed
Fixed: Fixed-time control
SCOOT: SCOOT control
INT S: INTEGRATION splits
INT SO: INTEGRATION splits and offsets
INT SC: INTEGRATION splits and cycles
INT SCO: Full INTEGRATION control

Vehicle Occupancies
Cass: 1.2 persons/vehicle
Buses: 40 persons/vehicle

Figure 4.3: Impact of Signal Control Alternatives on Traffic Performance (AM Peak)

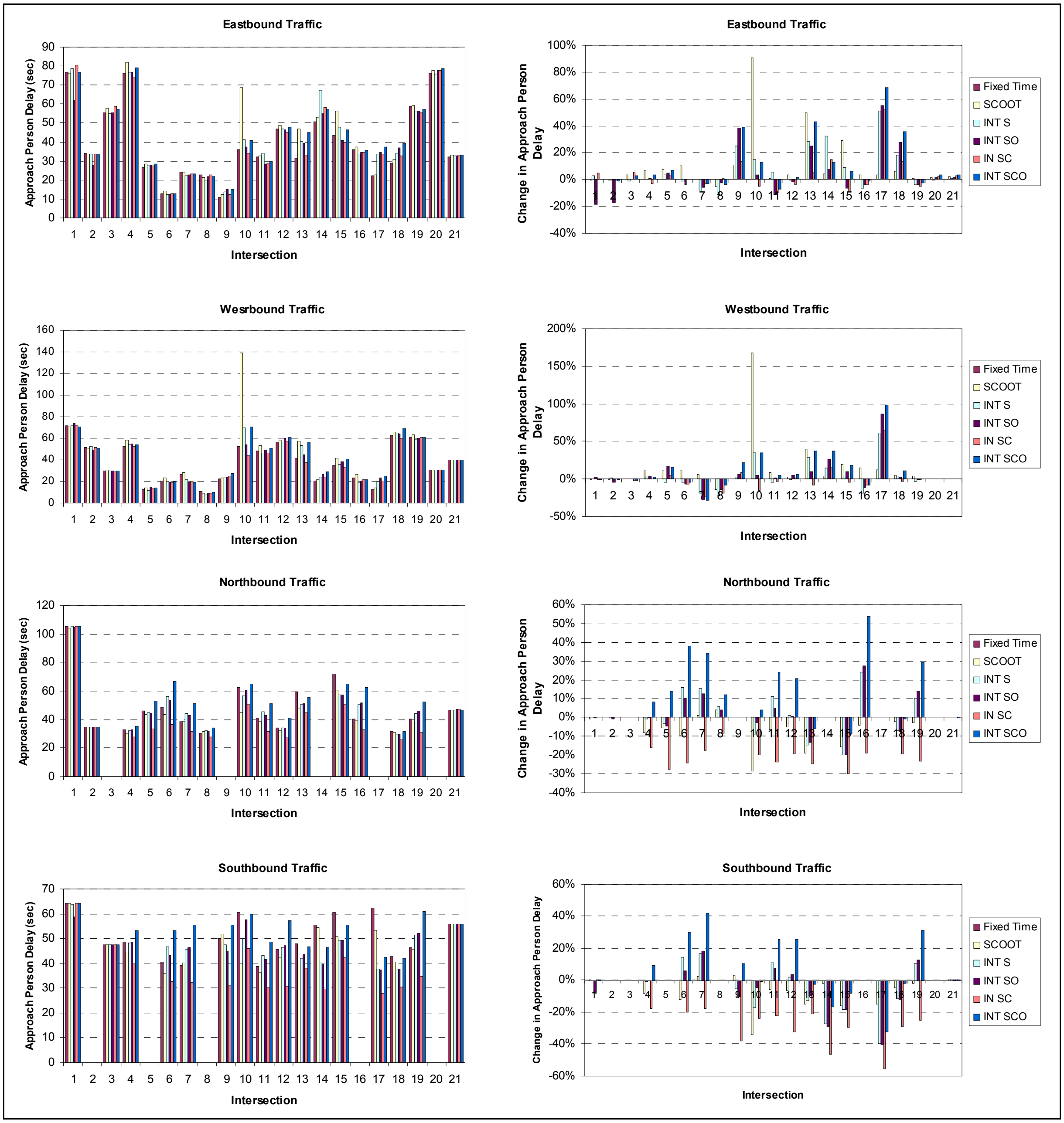


Figure 4.4: Impact of Signal Control Strategies on Intersection Approach Delays (AM Peak)

Glebe relatively constant green splits. In Figure 4.1, a first major difference exists between the fixed-time and SCOOT signal timings. In this case, it is observed that the SCOOT timings allocate significantly more green to the George Mason traffic than to the Columbia Pike traffic. While the fixed signal timing plan allocates 21 and 39% of the total green time to the Columbia Pike eastbound leading and main green phases, respectively, only 12 and 28% of the total green are allocated to the same phases under SCOOT control. Another major difference is found between the fixed and INTEGRATION timings. For this case, Figure 4.1 indicates that the INTEGRATION model shifts a significant portion of the green time initially allocated to the Columbia Pike main green to the arterial's leading green. This change is done to allow left-turning movements in the eastbound direction to be better served and does not result in a significant change in the overall amount of green time allocated to the eastbound traffic. However, it does reduce the green time allocated for the westbound traffic, which is the direction carrying the minor flow during the AM peak period.

On a performance point of view, the diagrams of Figure 4.3 further indicate that the signal control strategies considered did not always reduced overall vehicle delays, stops and fuel consumption, but that they generally reduced vehicle emissions. It is also observed that the best signal control strategy appears to be the one in which the INTEGRATION model is optimizing the both green split and offset of each intersection while using the 100-second arterial cycle time defined in Table 3.8. For this scenario, the signal control strategy specifically reduces overall delays by 2.0%, vehicle stops by 0.7%, fuel consumption by 1.0% and vehicle emissions by 1.1%. While the INTEGRATION Split-Cycle scenario produces much greater reductions in overall delay (10%), it also significantly increases vehicle stops (6.7%), HC emissions (5.1%), CO emissions (9.0%) and NOx emissions (4.6%).

Another element of particular interest in Figure 4.3 is the fact that the two signal control strategies in which all timing parameters are adjusted to observed traffic conditions, i.e., the SCOOT and INTEGRATION Split-Cycle-Offset strategies, produce the two worse scenarios in terms of delay:

- For the INTEGRATION Split-Cycle-Offset scenario, the increase in delay can be attributed to the use of longer cycle times than under fixed-time control. As illustrated in Figure 4.1 and Figure 4.2 for the intersections with George Mason and Glebe, this control strategy results in the use of a 130-second cycle instead of a 100-second cycle. While longer signal cycles typically increase traffic capacity, they also result in more delays. Figure 4.4 illustrates another contributing factor. This factor is the increased delay on the streets crossing Columbia Pike due to the implementation of less favorable green splits for these approaches under the INTEGRATION control strategy.
- For the SCOOT control scenario, the cycle time cannot be a contributing factor to the delay increase since Figure 4.2 indicates that the SCOOT system implemented a 104-second cycle, which is almost identical to the 100-second cycle defined in the fixed-time plan. In this case, Figure 4.4 and Figure 4.1 provide a good explanation for the delay increase. First, Figure 4.4 indicates that the SCOOT timings caused large delay increases on the eastbound and westbound approaches to the intersection with George Mason (91 and 168% increases, respectively). Figure 4.1 further indicates that these delay increases are likely caused by a reduction in the green time allocated to the Columbia Pike traffic when replacing the fixed timings of Table 3.8 by the SCOOT timings of Table 3.11. Since the same demand is simulated in both signal control scenarios, increased congestion thus logically results from the reduced green time on the Columbia Pike approaches.

After having reviewed the simulation results, some general concerns were further issued regarding the validity of the simulations using the modeled SCOOT signal timings of Table 3.11. First, while the SCOOT timings coded in INTEGRATION model the operation of the system as observed on June 13 and June 14, 2000, the demand that is controlled by these timings in the simulation is for its part based on manual counts that were conducted between June 6 and June 8, as well as on SCOOT detector data from June 12 and 14. Second, the modeled SCOOT timings are an average of the observed timings and remain fixed within each 15-minute simulation interval. They are not adjusted every cycle to the observed demand, as it is done in reality. Consequently, it is therefore possible, and very likely, that the demand being simulated in INTEGRATION does not entirely correspond to the demand that was observed on June 13 and 14 along Columbia Pike and that resulted in the implementation of the observed SCOOT timings. Because of the potential inconsistencies between actual and simulated traffic demands, it is therefore possible that the simulations using the modeled SCOOT timings of Table 3.11 did not allow the SCOOT signal control alternative to be fairly evaluated, thus commanding careful evaluations of the simulation results before drawing any general conclusions.

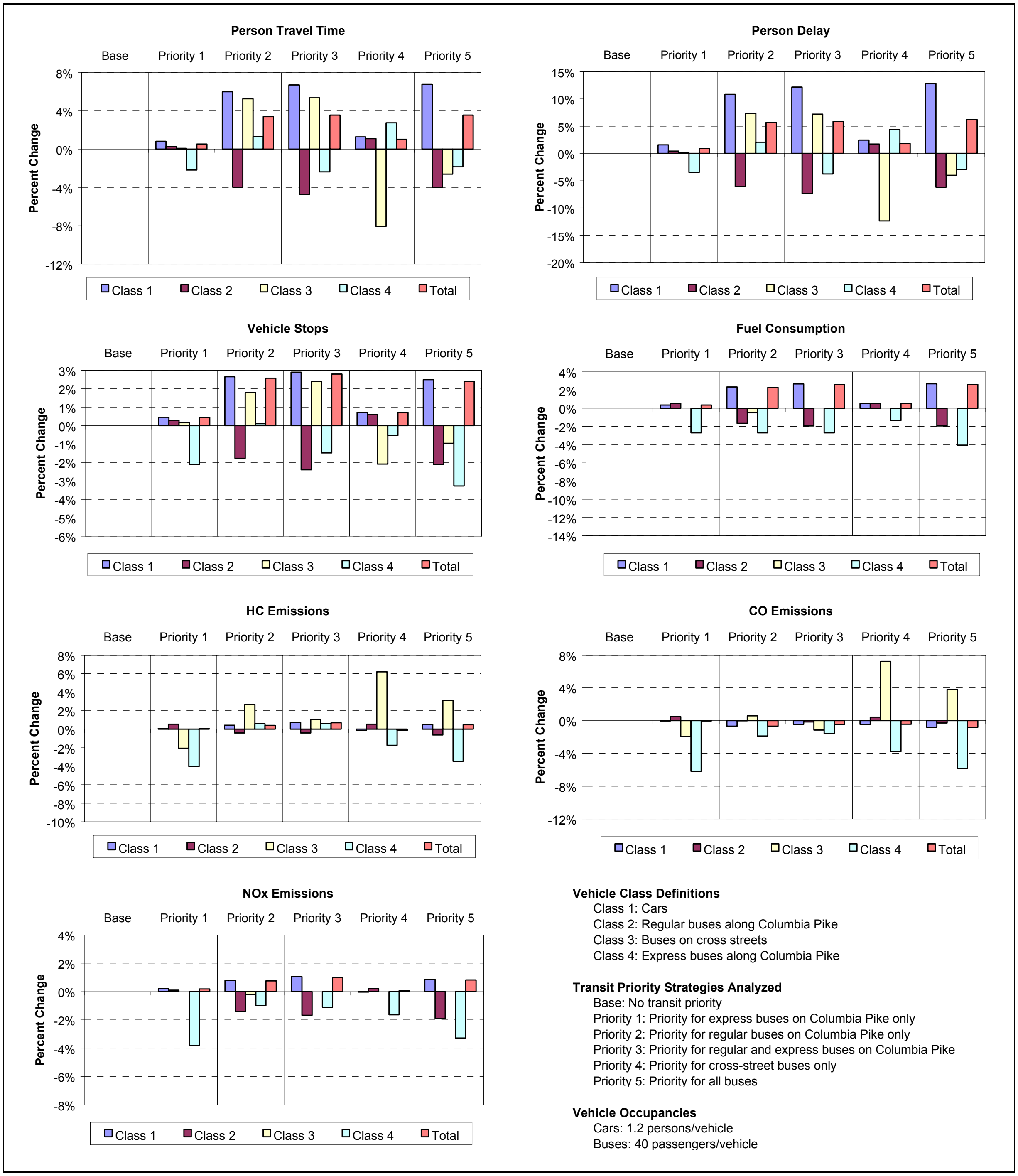
4.1.2 Priority under Fixed-Time Signal Control

For the fixed-time scenario, Figure 4.5 indicates that the implementation of transit priority only for the express buses traveling along Columbia Pike (Priority 1) provides benefits to these vehicles. For these vehicles, the implementation of an exclusive priority scheme results in a 3.5 % decrease in delay, a 2.1% decrease in the number of stops, a 2.7% decrease in fuel consumption, and reductions in emissions ranging from 3.8 to 6.2%. However, the figure also shows that the regular traffic generally suffers from this priority scheme. For these vehicles, a 1.6% increase in delay is observed, together with a 0.5% increase in stops, a 0.4% increase in fuel consumption, and increases in vehicle emissions that do not exceed 0.2%. While the increases in performance measures for the general traffic appear to be marginal, the observed increases are sufficient to produce overall negative results due to the much higher number of cars and non-prioritized buses traveling along the corridor than the number of prioritized buses.

Figure 4.6, which illustrates the overall changes in vehicle delay on individual intersection approaches, provides similar conclusions as Figure 4.5. The figure indicates that providing priority to express buses does not significantly reduce delays on intersection approaches along the corridor. Again, this result is mainly due to the low number of express buses traveling along the corridor, and thus, to the limited number of times that signal priority is requested. In the figure, the approaches with the most important changes in delay are the southbound approaches to the intersections with George Mason (26.4% increase) and Wayne (30.9% increase). At both intersections, the increase in delay is primarily due to the allocation of less green time to these approaches, which cause some congestion to appear.

Along Columbia Pike, Figure 4.6 indicates that delay reductions of up to 5.5% were obtained at some intersections, while delay increases of up to 9.3% are observed at other intersections. In particular, it is observed that single or small groups of approaches where the general traffic experience delay reductions are typically followed by approaches with delay increases. This is an indication that the cars that are able to benefit from the priority scheme at one intersection often lose this benefit at other intersections. While some vehicles are able to cross an intersection at the same time that a bus receives priority of passage, these vehicles will often reach the next intersection before the prioritized bus reaches. This happens because transit vehicles typically stop between signalized intersections to load and discharge passengers while private vehicles do not do so. Therefore, because of their earlier than expected arrival at the next intersection, these vehicles often have to wait for the next scheduled green to appear before being able to cross the intersection, or for the prioritized bus to reach the intersection and request again priority of passage.

When priority is offered to the regular buses traveling along Columbia Pike (Priority 2), similar changes in performance measures as described above are observed for the prioritized vehicles. As shown in Figure 4.5, this priority scheme generally produces benefits for the regular buses, but not necessarily for the express buses. While regular buses see their delay reduced by 7.1%, their number of stops and fuel consumption reduced by 2.0%, and their emissions reduced between 0.4 and 1.6%, express buses experience an increase in delay of 0.8%, a 0.8% reduction in their number of stops, a 2.7% reduction in fuel consumption, a 1.7% increase in HC emissions, virtually no change in CO emissions, and a 0.5% reduction in NO_x emissions. The general traffic, on the other hand, experience a 13.0% increase in delay, a 2.5% increase in the number of stops and fuel consumption, a 0.6% increase in HC emissions, a 0.6% decrease in CO emissions and a 0.8% increase in NO_x emissions. Again, given the high number of cars traveling along the corridor when compared to the number of prioritized buses, these increases are sufficient to yield overall negative results for the priority scheme.



Vehicle Class Definitions

Class 1: Cars
Class 2: Regular buses along Columbia Pike
Class 3: Buses on cross streets
Class 4: Express buses along Columbia Pike

Transit Priority Strategies Analyzed

Base: No transit priority
Priority 1: Priority for express buses on Columbia Pike only
Priority 2: Priority for regular buses on Columbia Pike only
Priority 3: Priority for regular and express buses on Columbia Pike
Priority 4: Priority for cross-street buses only
Priority 5: Priority for all buses

Vehicle Occupancies

Cars: 1.2 persons/vehicle
Buses: 40 passengers/vehicle

Figure 4.5: Impact of Priority on Traffic Performance under Fixed-Time Control (AM Peak)

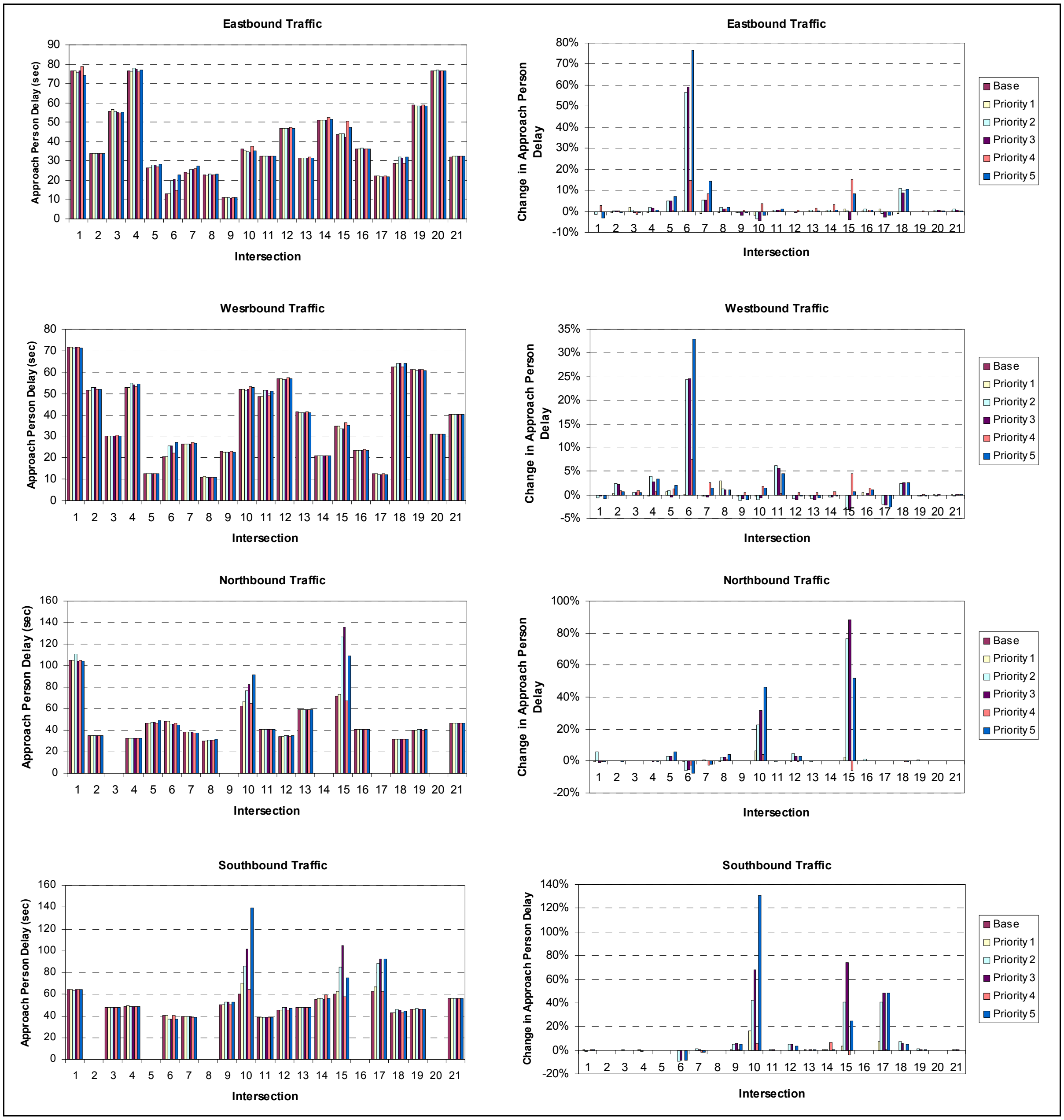


Figure 4.6: Impact of Priority on Approach Delays under Fixed-Time Control (AM Peak)

In this case, the delay increases for the express buses and general traffic are mostly attributed to the traffic congestion that appears around Buchanan following the implementation of transit priority. In Figure 4.6, the large delay increases for the eastbound and westbound approaches of Buchanan are directly caused by the signal switching decisions taken by the transit priority logic. To explain this conclusion, it must first be observed that the bus stop at the intersection with Four Mile Run in the eastbound direction is located near the intersection stop line (see Figure 3.6) and that the following bus stop is located just downstream of the intersection with Buchanan. It must also be indicated that at a few occasions during the simulations a bus that had just finished dwelling at the intersection with Four Mile Run would obtain an early green and start moving towards the next intersection while being at the front of a platoon of vehicles. Upon reaching the next intersection, this bus would call for another green extension. In some occasions, this change would be granted, but only maintained to let the bus pass, thus causing all the vehicles following the bus to stop and wait at the intersection until the next green signal. In addition to the increases delays at the intersection with Buchanan, Figure 4.6 also indicates increased delays for the northbound and southbound approaches to the intersections with George Mason, Walter Reed and Wayne. In this case, however, the observed increases are simply due to the decrease in green time allocated to these approaches.

When priority is offered to both the regular and express buses (Priority 3), results are generally similar to those associated with to the scenario offering priority to the regular buses only (Priority 2). For the regular buses, Figure 4.5 indicates that this priority scheme reduces delay by 7.3%, stops by 2.4%, fuel consumption by 1.9%, and vehicles emissions from 0.2 to 1.7%. For the express buses, this scheme decreases delay by 3.8%, stops by 1.5%, fuel consumption by 2.7%, and CO and NO_x emissions by 1.6 and 1.1%, respectively. For the regular traffic, it increase instead delays by 12.2%, stops by 2.9%, fuel consumption by 2.7% and HC and NO_x emissions by 0.7 and 1.1%.

For this priority scheme, the differences in performance measures for the regular and express buses are explained by the inability of the scheme to accommodate all buses at prioritized signalized intersections. In the simulation, express buses often end up following regular buses while approaching an intersection. On these approaches, the first buses would typically get priority, but not necessarily the second one due to constraints in the maximum allowable green extensions and early green recalls. For the general traffic, the additional reduction in green time allocated to the cross-street approaches of prioritized intersections due to the larger number of vehicles requesting priority of passage further explain the overall increases in delay, stops, fuel consumption and emissions along the corridor. This reduction in allocated green time also explains the sizeable increase in delay observed for the cross-street approaches of George Mason and Glebe in Figure 4.6. For the intersection with Buchanan, the problem caused the priority logic that was discussed earlier is again responsible for the large observed increases in delay along the eastbound and westbound approaches to this intersection.

When priority is offered to buses traveling on streets crossing Columbia Pike, significant benefits are obtained for these vehicles, but again at the expense of the general traffic and non-prioritized buses. For this priority scheme, reductions in delay and stops of 12.4 and 2.1% are obtained for the prioritized vehicles. No change in fuel consumption and NO_x emissions are observed, while HC and CO emissions increase by 6.2 and 7.2%. While this priority scheme also generally produces negative results for the vehicles traveling along Columbia Pike, the overall increases in delay, stops, fuel consumption and emissions remain moderate. For the overall traffic, the increase in delay is 2.4%, while the increases in stops, fuel consumption and emissions are less than 0.7%. Figure 4.6 indicates that congestion problems still occur at the intersections with Buchanan and George Mason, but that the problems that were observed on the cross-street approaches to the intersections with Glebe and Wayne in the other priority schemes have all disappeared as a result of having more green time allocated to these approaches.

Finally, offering priority to all buses generally benefit these vehicles, but also generally worsen traffic conditions along the corridor. While delay reductions of up to 6.2%, stop reductions of up to 3.3% and fuel consumption reductions of up to 4.1% are observed in Figure 4.5 for the various buses, delay, stop and fuel consumption increases of 12.8, 2.5

and 2.7%, respectively, are observed for the general traffic. In Figure 4.6, the problems associated with this priority scheme appear to be caused by increased traffic congestion at the intersections with Buchanan, George Mason, Glebe, and Wayne due to the frequent alterations that are made to the signal timings to accommodate the numerous approaching buses.

In overall, there does not appear to be a best scenario for transit priority under fixed-time control along the corridor. While the Priority 4 scenario provided the highest benefits for the prioritized vehicles, it only offers priority to buses traveling on the streets crossing Columbia Pike while the main intent of the project is to evaluate priority for buses traveling along Columbia Pike. Within the remaining scenarios, the scenarios with the higher benefits for the prioritized vehicles are also the ones having the highest negative impacts on the general traffic. When looking at the overall traffic conditions, the best scenario would thus be in this case the base scenario, i.e., the one considering offering priority to no vehicles at all

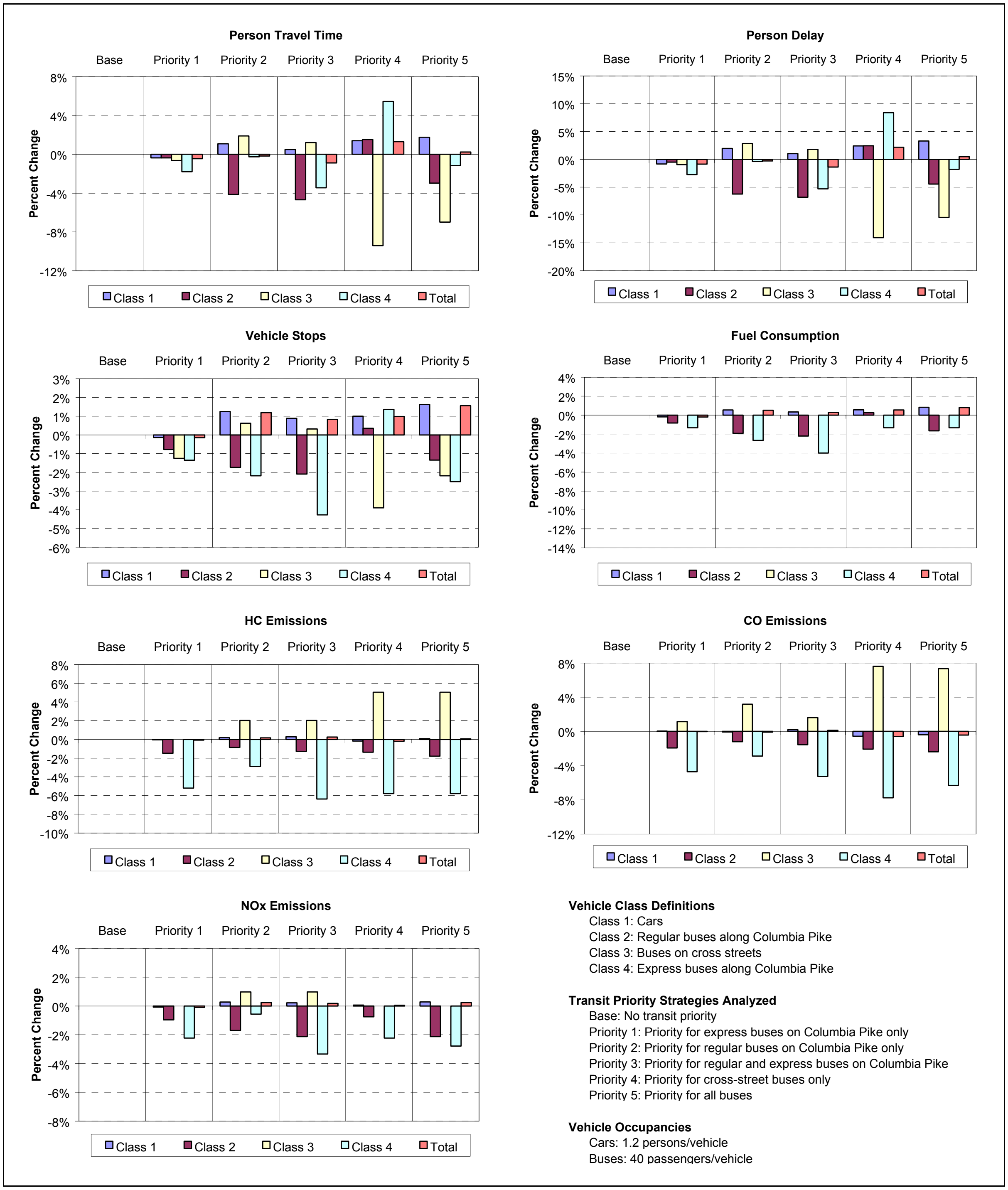
4.1.3 Priority under Observed SCOOT Control

Figure 4.7 and Figure 4.8 illustrate the results of the simulations that were conducted with the SCOOT timings of Table 3.11. For these scenarios, Figure 4.7 indicates that all priority schemes that consider only buses traveling along Columbia Pike slightly reduce the delays incurred by the general traffic. This was not an expected result. Given the adaptive nature of the SCOOT traffic signal control system, no delay reduction or small increases were expected to result from the disruptions caused by the implementation of sudden signal changes, similar to what had been observed in the fixed-time scenarios.

Figure 4.8 provides the answer to these unexpected results. When the figure is compared to Figure 4.6, similar levels of delays are observed for all intersection approaches, except for the intersection with George Mason. For this intersection, the use of SCOOT timings result in almost twice as much delay for the eastbound approach than under fixed-time control. These timings also result in a 300% increase in delay for the westbound approach, and approximately 33% less delays for the northbound and southbound approaches. Similar to the conclusions that were reached in Section 8.1 when comparing traffic performance under SCOOT and fixed-time control, it is determined that the observed changes in delay are caused by a shift in the allocated green between the fixed-time and simulated SCOOT timings. Given that all simulations consider the same traffic demand, the reduced green time allocated to the eastbound and westbound approaches thus explains the increased congestion observed on these approaches in the base SCOOT scenario when compared to the base fixed-time scenario. Similarly, the increased green time allocated to the intersection's cross-streets explain the improved traffic performance on these approaches.

In this case, providing priority to the buses traveling along Columbia Pike improves the overall traffic conditions at the intersection with George Mason by favorably adjusting the green split. Since the priority schemes would typically increase the green time allocated to the congested eastbound and westbound approaches, they would therefore help reducing the congestion and improving general traffic conditions on these approaches. This observation leads to the conclusion that transit priority can sometimes help improving traffic conditions at signalized intersections with non-optimal timings.

While concerns can be raised regarding the validity of the simulated flows with respect to the simulated SCOOT timings, it is generally observed in Figure 4.7 that the implementation of the various priority schemes typically benefits the prioritized buses. Depending on the scenario considered, prioritized buses experience delay reductions ranging from 1.8 to 14.1%, stop reductions ranging from 1.4 to 4.3%, economy in fuel consumption ranging from 0 to 4.0%, and changes in emissions ranging from a 7.6% increase to a 6.4% decrease. The general traffic, on the other hand, experiences changes in delay ranging from a 2.4% increase, when priority is given to the cross-street buses, to a 0.8% reduction when only the express buses are prioritized. It also experiences changes in the number of stops ranging from a 0.1% decrease to a 1.6% increase, while fuel consumption and vehicle emissions typically vary by less and 1.0%, either on the increase or decrease side.



Vehicle Class Definitions
Class 1: Cars
Class 2: Regular buses along Columbia Pike
Class 3: Buses on cross streets
Class 4: Express buses along Columbia Pike

Transit Priority Strategies Analyzed
Base: No transit priority
Priority 1: Priority for express buses on Columbia Pike only
Priority 2: Priority for regular buses on Columbia Pike only
Priority 3: Priority for regular and express buses on Columbia Pike
Priority 4: Priority for cross-street buses only
Priority 5: Priority for all buses

Vehicle Occupancies
Cars: 1.2 persons/vehicle
Buses: 40 passengers/vehicle

Figure 4.7: Impact of Priority on Traffic Performance under Average Observed SCOOT Control (AM Peak)

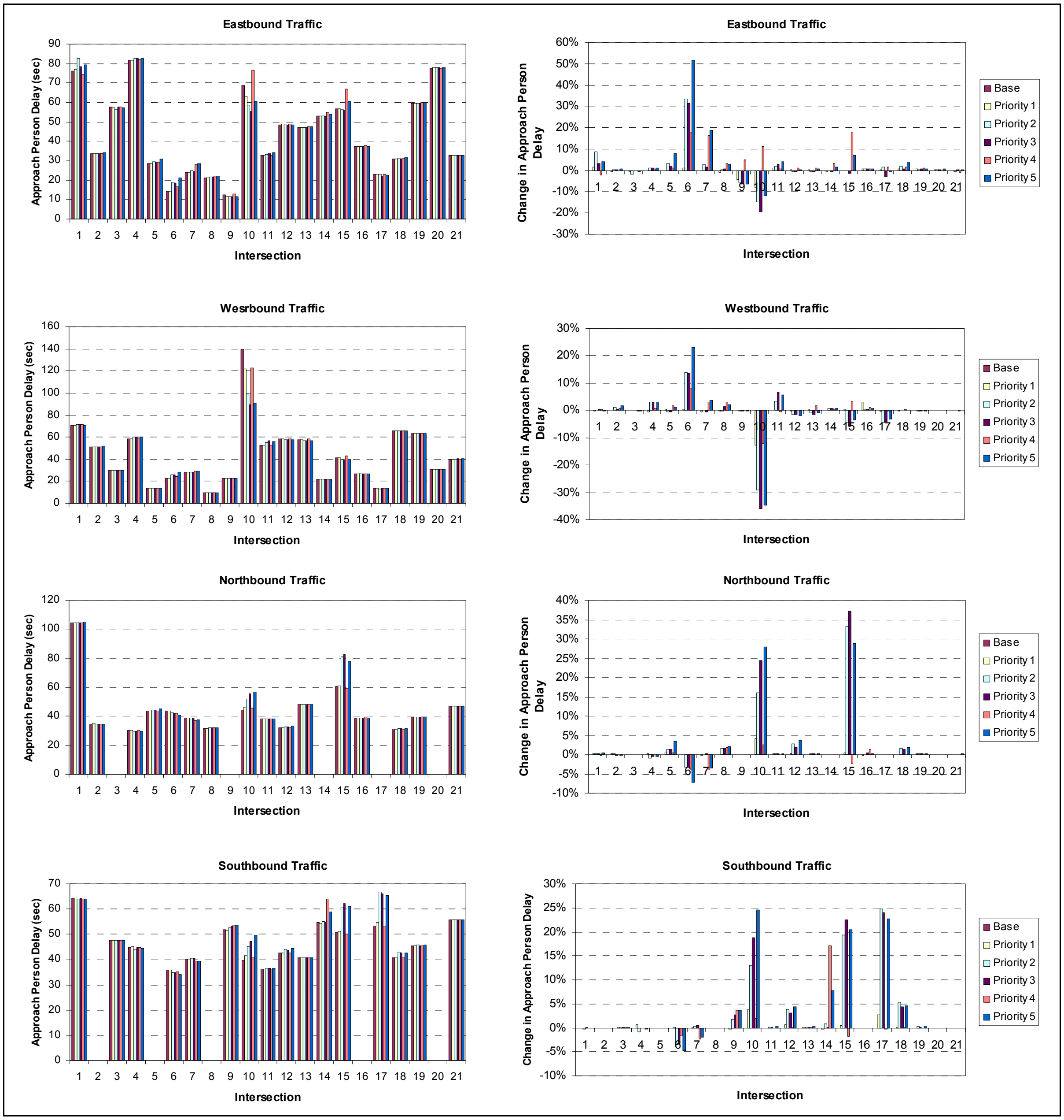


Figure 4.8: Impact of Priority on Approach Delays under Average Observed SCOOT Control (AM Peak)

Similar to the fixed-time scenarios, it is also generally observed that priority scenarios with high benefits for the prioritized vehicles are also scenarios having the highest negative impacts on the general traffic. Contrary to the fixed-time results, the best scenario appears to be in this case the one providing priority only to express buses traveling along Columbia Pike (Priority 1). The next best scenario is the base scenario, i.e., the one providing priority to no vehicles at all. At the other end, the worse overall scenario is the one providing priority to all buses traveling along the corridor.

4.1.4 Priority with INTEGRATION Split Control

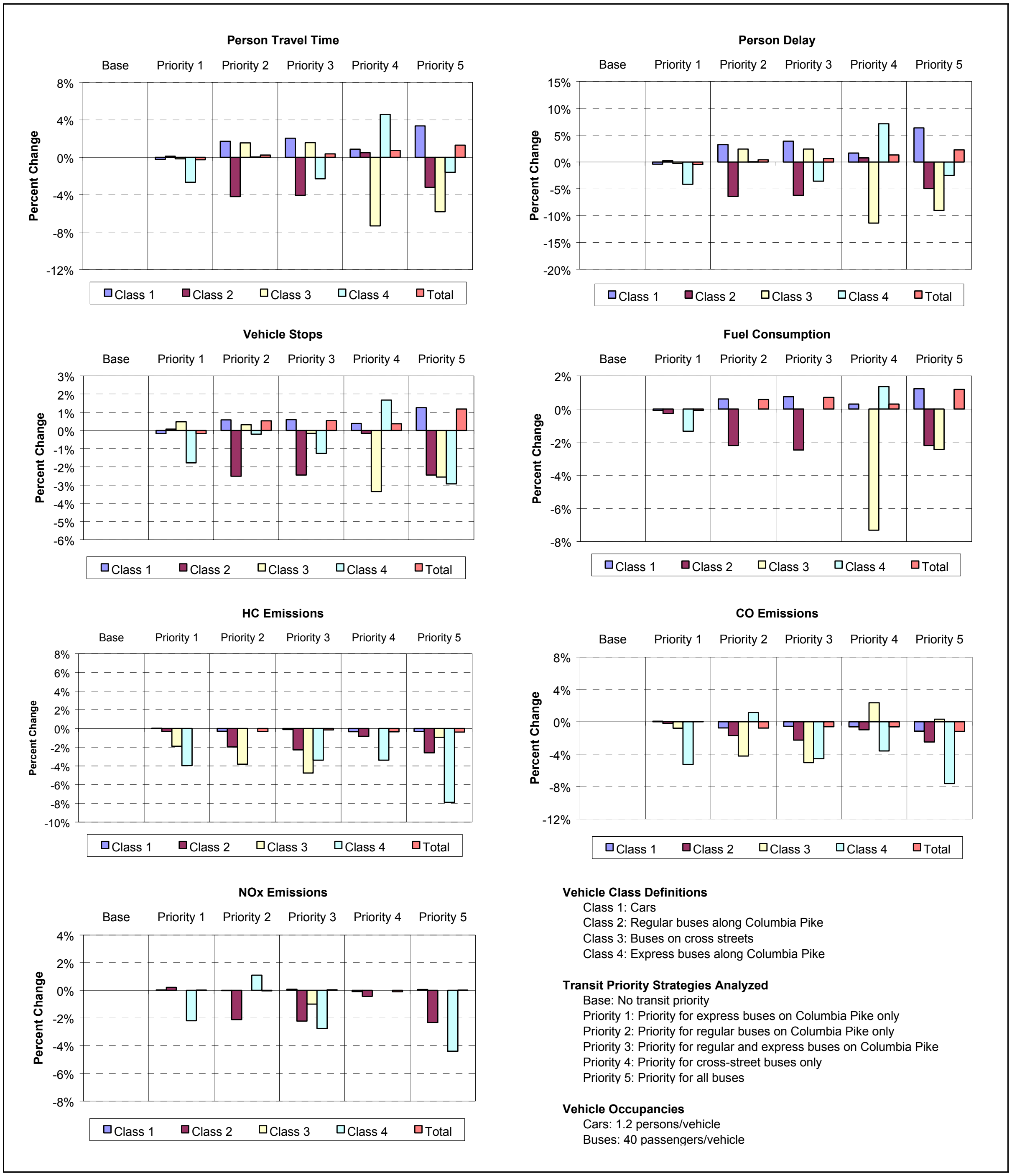
When the INTEGRATION model is allowed to determine every five-minutes the green splits at SCOOT-controlled intersections instead of using the green splits defined in the MONARC timings of Table 3.8, benefits that are generally similar to those that were observed for the fixed-time control scenarios are obtained. Figure 4.9 and Figure 4.10 clearly illustrate this similarity:

First, similar to the results of Figure 4.5, Figure 4.9 indicates that the prioritized vehicles benefit from every priority scheme considered. Depending on the scheme considered, prioritized buses experience delay reductions varying between 2.5 and 11.4%, stop reductions varying between 1.3 and 3.4%, reductions in fuel consumption ranging from 0 to 7.3%, and reductions in vehicle emissions ranging between 0 and 7.3%. Only one scenario saw an increase in vehicle emissions for the prioritized buses: the scenario giving priority to cross-street buses, where these vehicles experienced a 2.3% in CO emissions.

Second, Figure 4.9 indicates that the general traffic did not benefit from the priority schemes, expect for the scenario considering priority to the express buses only. In this scenario, the general traffic benefit ed from a marginal 0.4% decrease in delay, a 0.2% decrease in the number of stops, and almost no change in fuel consumption and emissions. In all the other scenarios, the general traffic experienced delay increases ranging between 1.7 and 6.3%, stop and fuel consumption increases ranging between 0.4 and 1.3%, as well as reductions vehicle emissions that do not exceed 1.1%.

Finally, Figure 4.10 indicates that the intersection approaches with the largest delay increases after the implementation of the various transit priority schemes are the same as those of Figure 4.6. Similar to the fixed-time scenarios, the delay increases at the eastbound and westbound approaches to the intersection with Buchanan are explained by the decisions implemented by the transit priority logic simulated by INTEGRATION, while the increases on both the northbound and southbound approaches to George Mason, Glebe and Wayne are again explained by reductions in green time allocated to the cross-streets due to numerous the priority requests that are issued by buses along Columbia Pike.

The main difference between these results and the fixed-time scenario results is a reduced negative impact from the implementation of the various transit priority schemes under INTEGRATION Split control. As an example, it was indicated that the general traffic experiences under INTEGRATION Split control delay and stop increases of up to 6.8 and 1.3%, respectively, under the various priority scenarios considered. For the fixed-time scenarios, the increases were 12.8 and 2.9%, respectively, about twice as much as the increases under INTEGRATION Split control. A similar trend in reduced negative impacts is observed for the fuel consumption and vehicle emissions. This trend is explained by the adaptive nature of the INTEGRATION green split control. As explained earlier, the INTEGRATION signal optimization routines attempt to emulate the operations of a SCOOT system. Since the INTEGRATION model is programmed to modify the green splits of individual intersections at regular intervals to adjust them to observed traffic conditions within the simulation, it is therefore able to temporarily modify the green split of individual intersections to reduce any congestion that might have been caused by an earlier signal priority change. Because of this adaptive ability to react to changes in observed traffic conditions, it is therefore normal to obtain less negative effects under adaptive traffic signal control than under fixed-time control when considering transit priority.



Vehicle Class Definitions
- Class 1: Cars
- Class 2: Regular buses along Columbia Pike
- Class 3: Buses on cross streets
- Class 4: Express buses along Columbia Pike

Transit Priority Strategies Analyzed
- Base: No transit priority
- Priority 1: Priority for express buses on Columbia Pike only
- Priority 2: Priority for regular buses on Columbia Pike only
- Priority 3: Priority for regular and express buses on Columbia Pike
- Priority 4: Priority for cross-street buses only
- Priority 5: Priority for all buses

Vehicle Occupancies
- Cars: 1.2 persons/vehicle
- Buses: 40 passengers/vehicle

Figure 4.9: Impact of Priority on Traffic Performance under INTEGRATION Split Control (AM Peak)

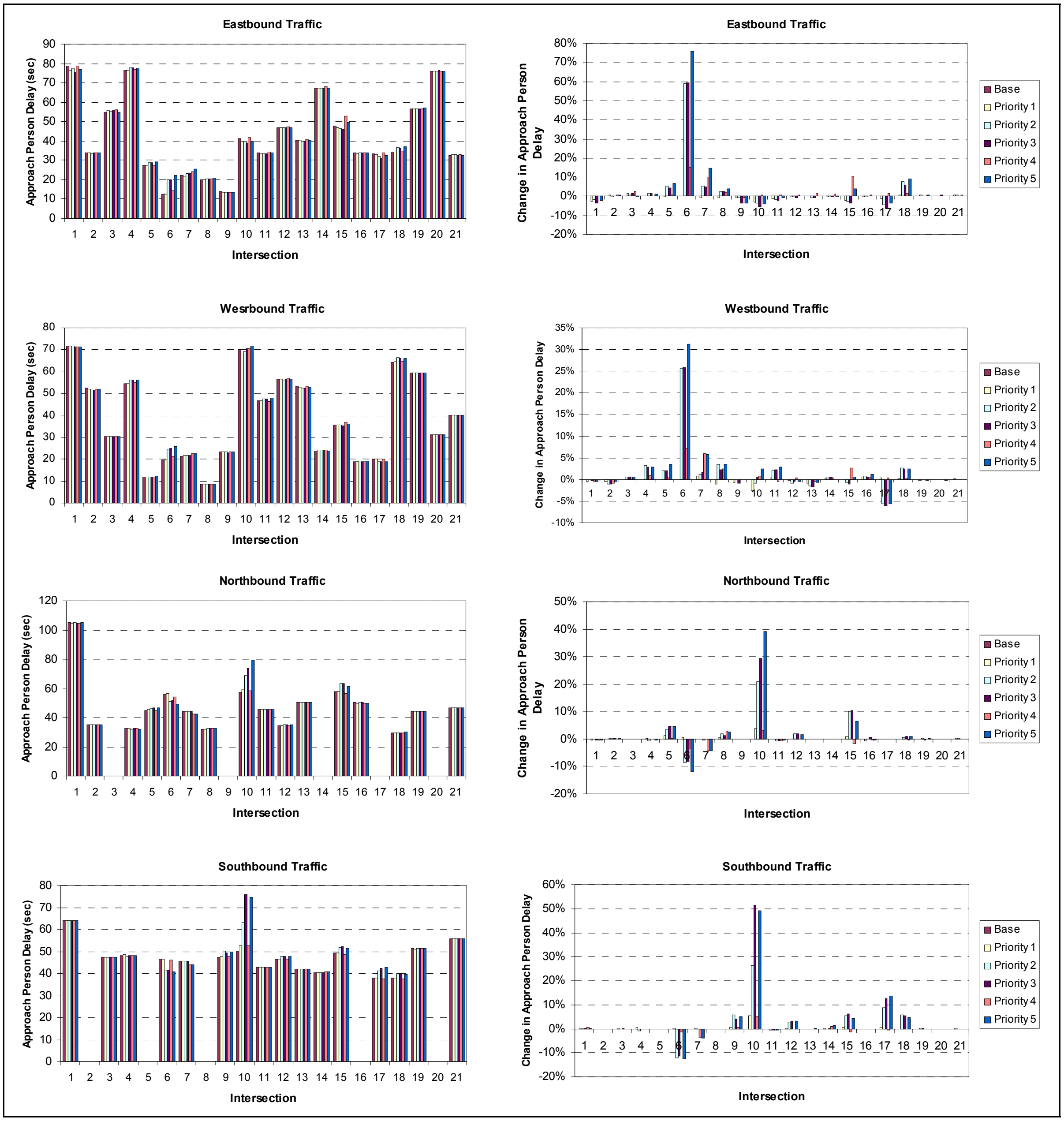


Figure 4.10: Impact of Priority on Approach Delays under INTEGRATION Split Control (AM Peak)

Similar to the previous scenarios, it is observed that the priority scenarios with the high benefits for the prioritized vehicles are also those having the highest negative impacts on the general traffic. When considering the overall traffic conditions, the best scenario appears to be the one providing priority only to express buses traveling along Columbia Pike (Priority 1). This is similar to the SCOOT results. The next best scenario is then the base scenario, i.e., the one providing priority to no vehicles at all. At the other end, the worse scenario is again the one providing priority to all buses traveling along the corridor. This scenario increases overall passenger delays, stops and fuel consumption along the corridor by 2.2, 1.2 and 1.2%, respectively, while slightly reducing vehicles emissions.

4.1.5 Priority with INTEGRATION Split and Offset Control

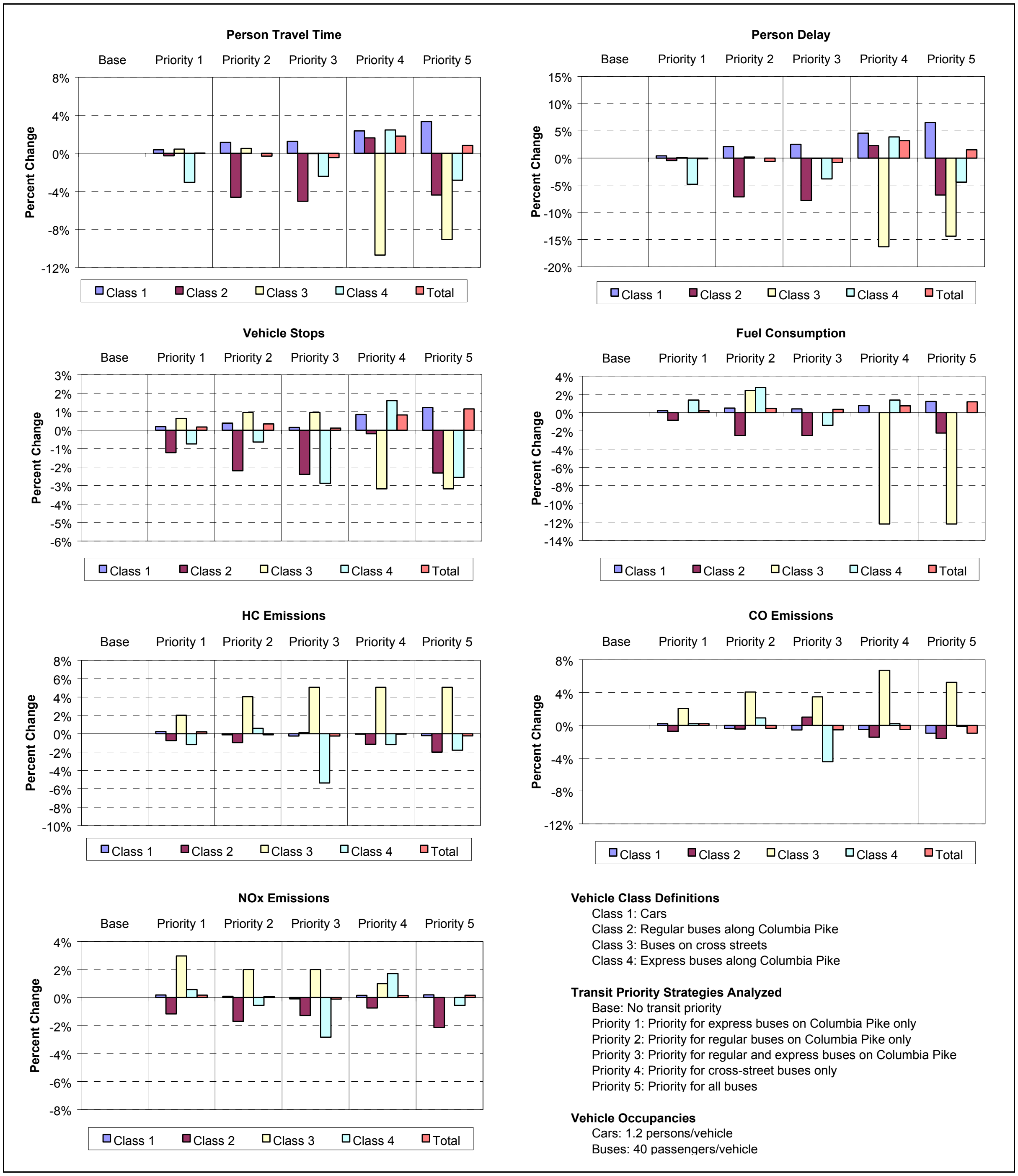
When INTEGRATION is allowed to determine every five-minutes both the green split and signal offset at SCOOT-controlled intersections, benefits that are generally similar to the INTEGRATION Split scenarios are obtained:

- First, Figure 4.11 indicates that all the priority schemes that were considered generally provide benefits to the prioritized vehicles. In this case, the prioritized buses experienced delay reductions varying between 3.8 and 16.3% and stop reductions varying between 1.7 and 3.2%. They also experience changes in fuel consumption ranging from a 1.4% increase (Priority 1) to a 12.2% reduction (Priority 4), and changes in vehicle emissions ranging from a 0.7% increase (CO, Priority 4) to a 5.4% decrease (HC, Priority 3, express buses).
- Second, Figure 4.11 indicates that the general traffic does not benefit from any of the priority schemes evaluated, except when considering vehicle emissions. In all the schemes considered, the general traffic experienced delay increases ranging from 0.4 to 6.5%, and stop and fuel consumption increases ranging from 0.2 to 1.2%. For the vehicle emissions, the various transit priority schemes generally reduced the HC, CO and NO_x emissions by amounts that did not exceed 1.0%. The only case for which there was an increase in emissions in the scheme

providing priority to the express buses only (Priority 1), in which NO_x emissions for the general traffic are slightly increased by 0.2%.

- Finally, Figure 4.12 indicates that the intersection approaches with the largest delay increases after the implementation of transit priority are the same as the other signal control scenarios: the intersections with Buchanan, George Mason, Glebe and Wayne. Similar to the fixed-time and INTEGRATION Split scenarios, the delay increases at the eastbound and westbound approaches to the intersection with Buchanan are primarily caused by the decisions implemented by the transit priority logic simulated by INTEGRATION. Furthermore, the increases on both the northbound and southbound approaches to George Mason, Glebe and Wayne are also again explained by reductions in allocated green time to the cross-streets due to the numerous transit priority requests that are issued by buses traveling along Columbia Pike. Finally, the delay increases and decreases that are observed in this case at the intersection with Carlin Spring are due to simulation factors as transit priority was not implemented at this intersection, neither than at its two neighboring intersections.

In this case, it is generally observed that the impact of allowing INTEGRATION to determine the signal offset in addition to the green splits is relatively small. When comparing Figure 4.11 and Figure 4.9, the only major differences are the larger reductions in delay, fuel consumption for the cross-street buses under the Priority 4 and Priority 5 scenarios, as well as the increased vehicle emissions for these buses in almost all priority scenarios.



Vehicle Class Definitions
Class 1: Cars
Class 2: Regular buses along Columbia Pike
Class 3: Buses on cross streets
Class 4: Express buses along Columbia Pike

Transit Priority Strategies Analyzed
Base: No transit priority
Priority 1: Priority for express buses on Columbia Pike only
Priority 2: Priority for regular buses on Columbia Pike only
Priority 3: Priority for regular and express buses on Columbia Pike
Priority 4: Priority for cross-street buses only
Priority 5: Priority for all buses

Vehicle Occupancies
Cars: 1.2 persons/vehicle
Buses: 40 passengers/vehicle

Figure 4.11: Impact of Priority on Traffic Performance under INTEGRATION Split-Offset Control (AM Peak)

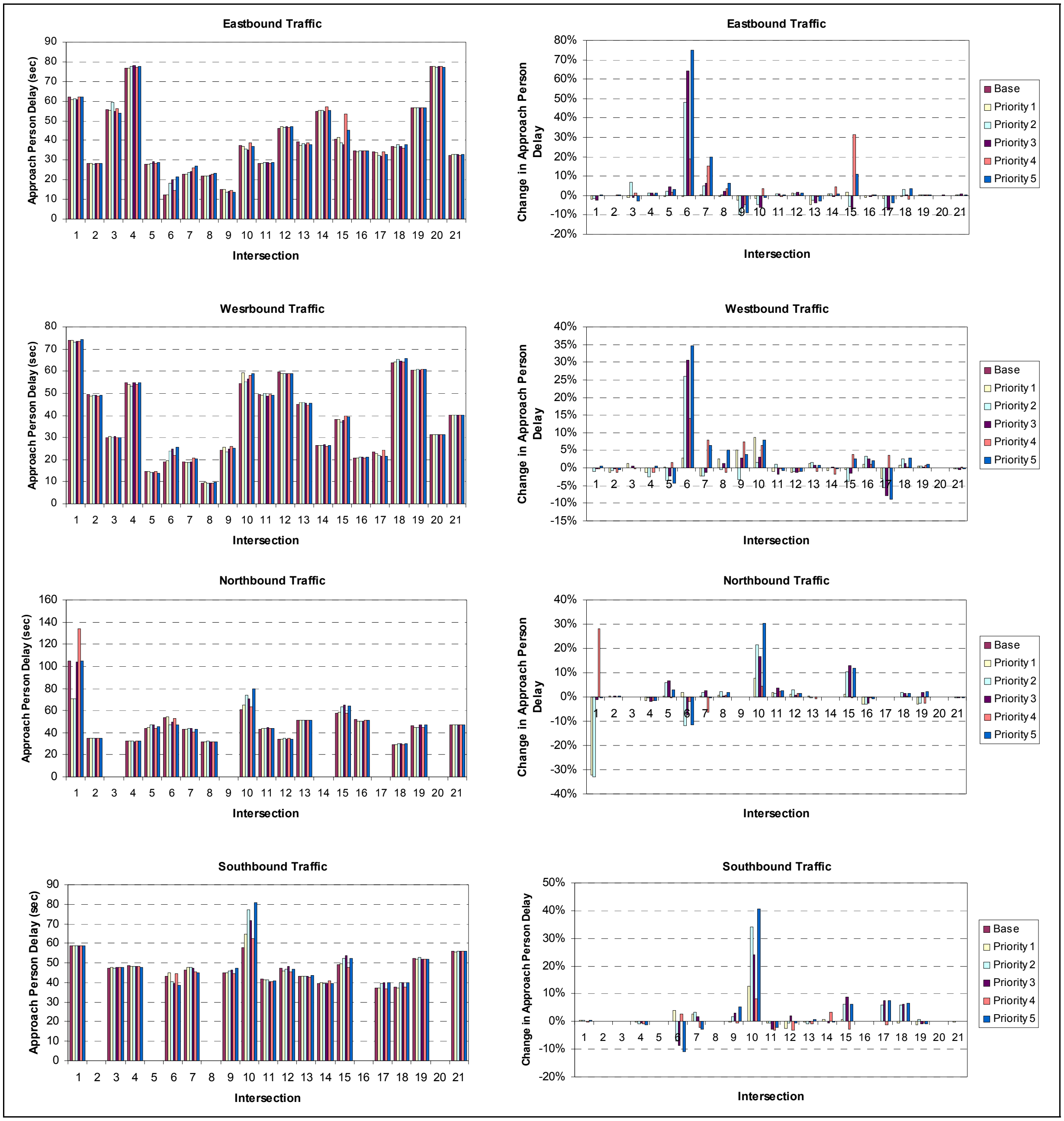


Figure 4.12: Impact of Priority on Approach Delays under INTEGRATION Split-Offset Control (AM Peak)

Overall, it is observed that the priority scenarios with high benefits for the prioritized vehicles are again the scenarios having the highest negative impacts on the general traffic when considering the benefits to all vehicles. However, the scenario providing priority to all buses traveling along Columbia Pike (Priority 3) could also be selected as the best scenario if person delay is the only performance measure considered. While this scenario increases general traffic delays by 2.5%, the delay reductions obtained by the prioritized buses are sufficient, under the assumption that buses carry 40 persons on average and cars 1.2 persons, to produce an overall delay reduction of 0.8%. At the other end, the worse scenario is again the one providing priority to all buses traveling along the corridor. This clearly indicates that there is a certain limit in the number of priority requests that a signal control system can efficiently handle under a given set of traffic conditions.

4.1.6 Priority with INTEGRATION Split and Cycle Control

Figure 4.13 and Figure 4.14 summarize the benefits that are obtained when INTEGRATION is allowed to determine every five-minutes both the green split and signal cycle at SCOOT-controlled intersections. When analyzing the results, the following observations can be made:

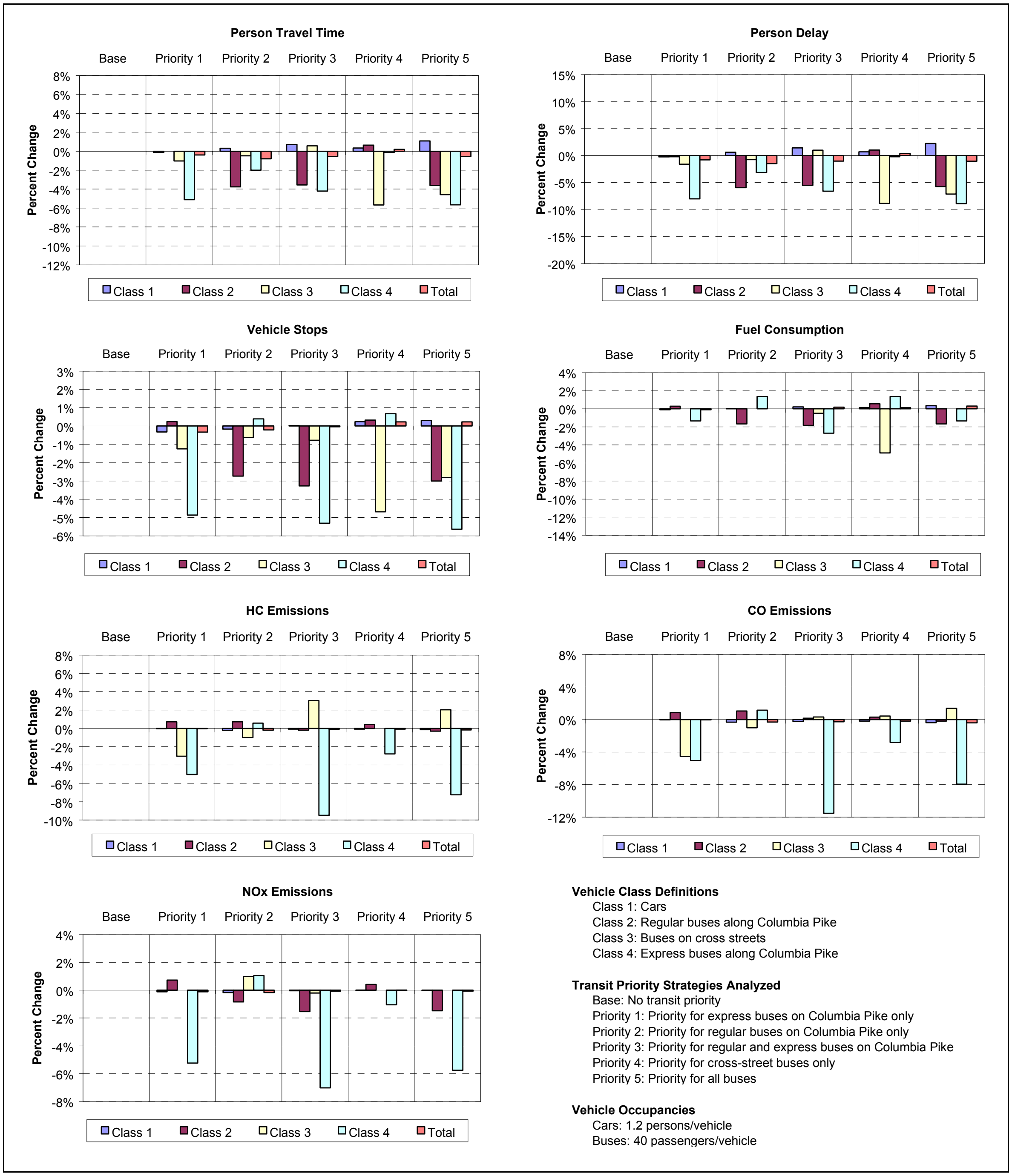
- Similar to the previous scenarios, Figure 4.13 indicates that the prioritized vehicles benefit from all the priority schemes considered. In this case, the prioritized buses experienced delay reductions varying between 5.5 and 8.9% and stop reductions varying between 2.7 and 5.6%. They also experience reductions in fuel consumption ranging from 1.4 to 4.9% and changes in vehicle emissions ranging from a 2.0% (HC, Priority 5, cross-street buses) increase to a 9.5% decrease (HC, Priority 3, express buses).
- In this case, Figure 4.13 indicates that the general traffic slightly benefits from both the scenario providing priority to the express buses only (Priority 1) and the regular buses only (Priority 2), but does not benefit from any of the other priority schemes. In the Priority 1 scenario, the general traffic experiences marginal delay

and stop reductions of 0.3%, as well as reductions in fuel consumption and vehicle emissions of 0.1%. Under the Priority 2 scenario, the general traffic experiences a delay increase of 0.6%, a stop reduction of 0.2%, no change in fuel consumption, and reductions in emissions of up to 0.3%. In the other scenarios, the general traffic experiences delay increases of up to 2.2%, stop and fuel consumption increases of up to 0.4%, and reductions in emissions of up to 0.4%.

- Finally, Figure 4.14 indicates that the intersection approaches with the largest delay increases after the implementation of transit priority are generally the same as before: the intersections with Buchanan, George Mason, Glebe and Wayne.

In this case, allowing the INTEGRATION model to determine the both the green split and signal cycle resulted in a series of priority scenario exhibiting the largest stop and emission reductions for the prioritized vehicles and the lowest negative impacts for the non-prioritized vehicles. This is very apparent when the results of Figure 4.5, Figure 4.7, Figure 4.9, Figure 4.11 and Figure 4.13 are compared. In particular, it is observed in Figure 4.13 that the increase in delay for the general traffic under any priority scheme never exceeds 2.2%, the increase in stops 0.2%, and the increase in fuel consumption 0.4%. Vehicle emissions are also reduced for all priority schemes considered. In the other signal control scenarios, much larger increases are observed for some of the priority schemes.

Referring back to Figure 4.1 and Figure 4.2, which illustrate the timings associated with each signal control scenario at the intersections with George Mason and Glebe, the above results can be explained by the short signal cycles that are implemented by the INTEGRATION signal optimization routines for this particular signal control scenario. While the MONARC fixed-time plan defines a network cycle length of 100 seconds and the SCOOT system varies the arterial cycle between 92 and 104 seconds, the INTEGRATION model implements cycles at individual intersections that typically vary in length between 45 and 50 seconds. This corresponds to about half the fixed and SCOOT cycle times and effectively creating a double-cycle operation. These shorter cycles directly explain the reduced negative in impacts in terms of increased delays that



Vehicle Class Definitions
Class 1: Cars
Class 2: Regular buses along Columbia Pike
Class 3: Buses on cross streets
Class 4: Express buses along Columbia Pike

Transit Priority Strategies Analyzed
Base: No transit priority
Priority 1: Priority for express buses on Columbia Pike only
Priority 2: Priority for regular buses on Columbia Pike only
Priority 3: Priority for regular and express buses on Columbia Pike
Priority 4: Priority for cross-street buses only
Priority 5: Priority for all buses

Vehicle Occupancies
Cars: 1.2 persons/vehicle
Buses: 40 passengers/vehicle

Figure 4.13: Impact of Priority on Traffic Performance under INTEGRATION Split-Cycle Control (AM Peak)

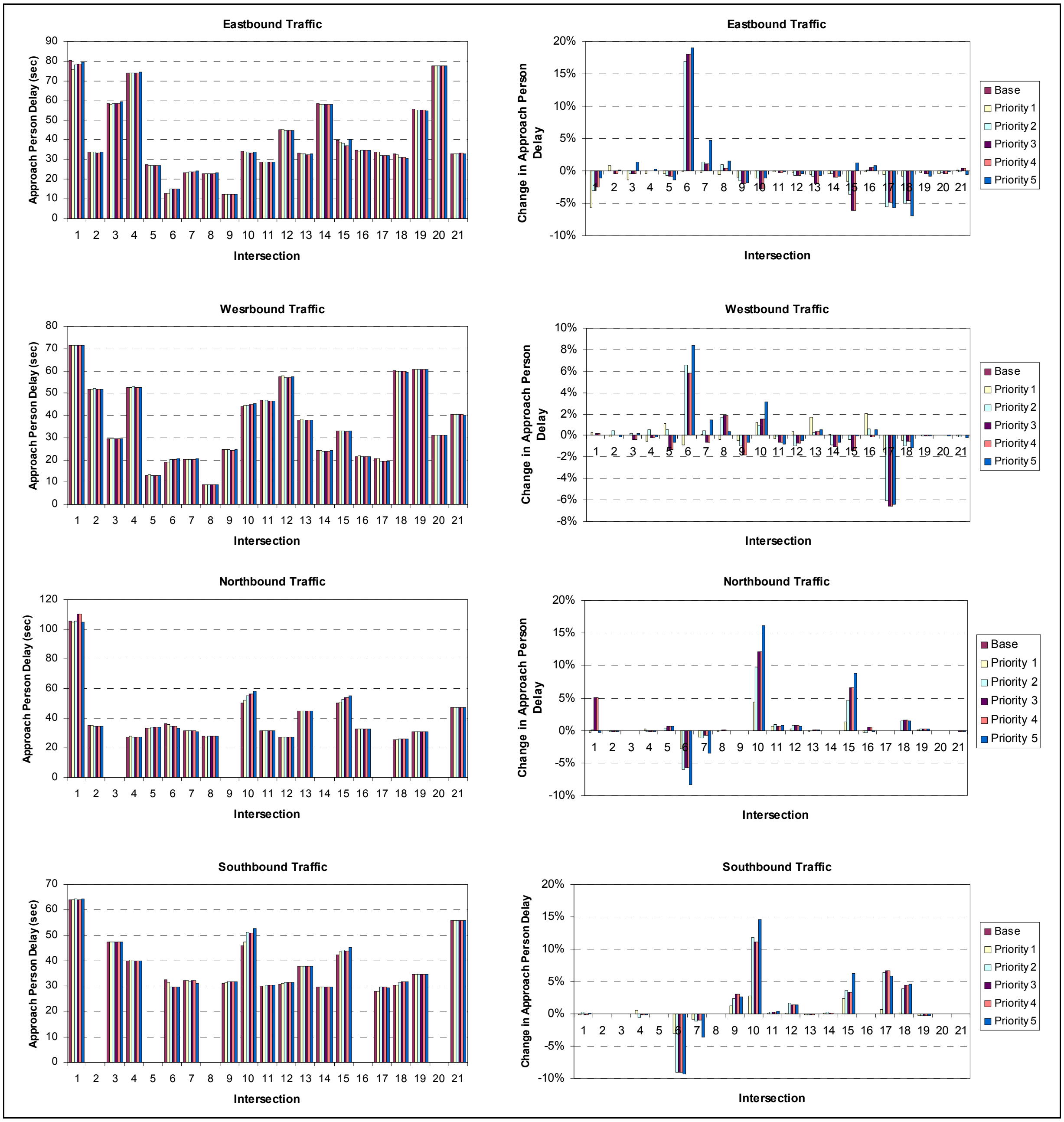


Figure 4.14: Impact of Priority on Approach Delays under INTEGRATION Split-Cycle Control (AM Peak)

are observed for the various priority schemes considered, as shorter cycles typically result in less waiting and less delays. The changes in vehicle stops, fuel consumption and vehicle emissions can similarly be explained by changes in traffic behavior caused by the implementation of shorter cycles.

In overall, it is again observed that the priority schemes with high benefits for the prioritized vehicles are typically the ones having the highest negative impacts on the general traffic. In this case, the scheme providing priority to all buses traveling along Columbia Pike (Priority 3) appears to be the best one. The base scenario, together with the schemes considering only either the express of regular buses traveling along Columbia Pike (Priority 1 and Priority 2), further appear to be good scenarios. As observed before, the worse scenario is either the one providing priority to the cross-street buses (Priority 4) or the one prioritizing all buses (Priority 5). These results, when compared to the results of the previous signal control scenario, thus confirms that there is a practical limit on the number of signal changes that can be awarded for prioritized vehicles.

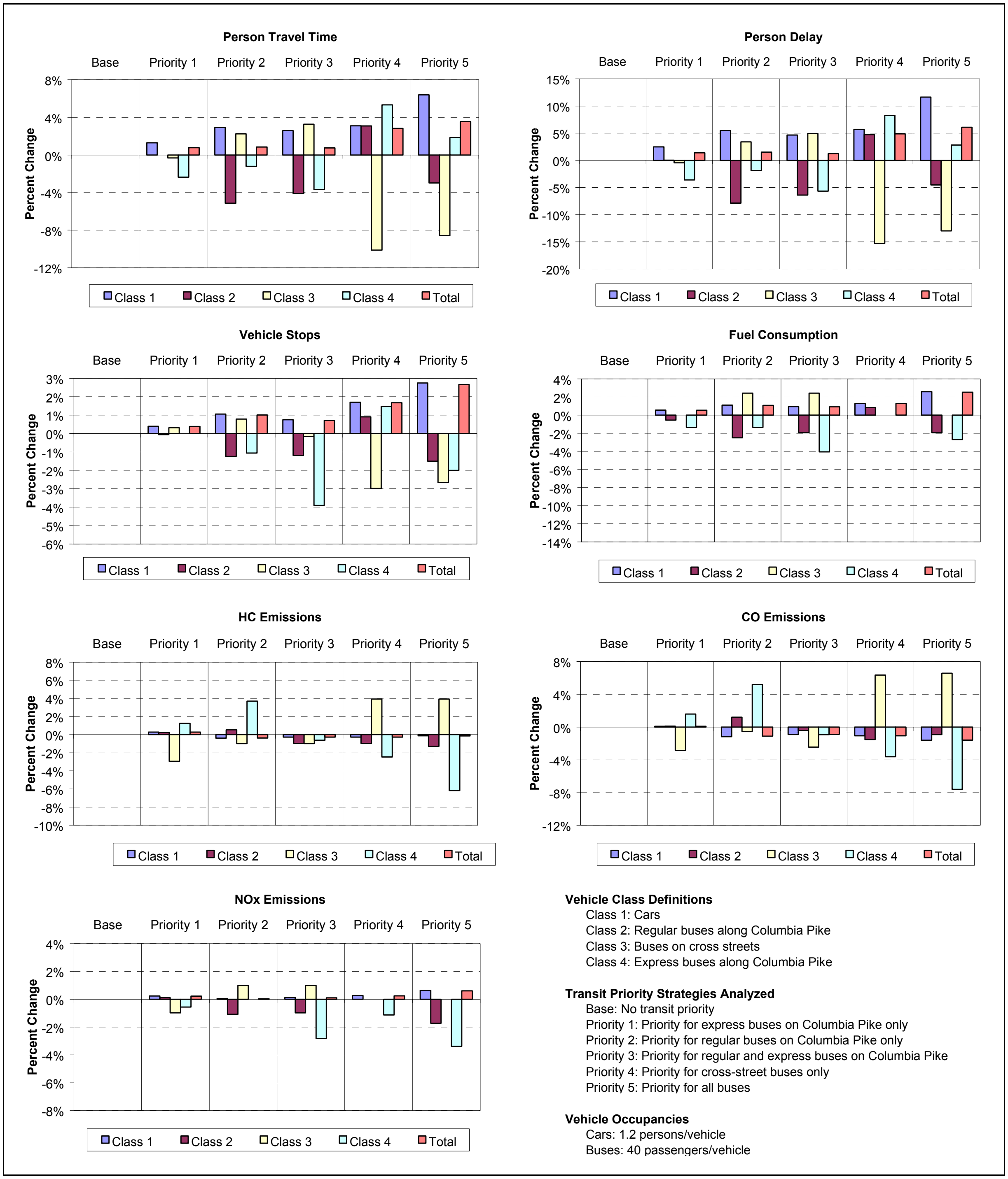
4.1.7 Priority with INTEGRATION Split, Offset and Cycle Control

Finally, when the INTEGRATION model is allowed to determine every five-minutes the green split, signal offset and cycle time at all SCOOT-controlled intersections, benefits that are generally similar but slightly better than those that were observed for the fixed-time scenarios are obtained:

- Similar to the all the scenarios considered, Figure 4.11 indicates that the prioritized vehicles benefit from all the priority schemes considered. With small exceptions, the prioritized buses experienced delay reductions varying between 3.6 and 13.0%, stop reductions of up to 3.9%, reductions in fuel consumption of up to 4.1%, and changes in vehicle emissions ranging from a 7.6% reduction to a 6.6% increase.

- Figure 4.11 indicates that the general traffic does not benefit from any of the priority schemes considering. In this case, the general traffic experience delay increases varying between 2.5 and 11.7%, stop increases varying between 0.4 and 2.7%, fuel consumption increases varying between 0.5 and 2.6%, and changes in vehicle emissions ranging from a 0.6% increase to a 1.9% decrease.

- Finally, Figure 4.15 indicates that the intersection approaches with the largest delay increases after the implementation of transit priority are again the intersections with Buchanan, George Mason, Glebe and Wayne.



Vehicle Class Definitions
Class 1: Cars
Class 2: Regular buses along Columbia Pike
Class 3: Buses on cross streets
Class 4: Express buses along Columbia Pike

Transit Priority Strategies Analyzed
Base: No transit priority
Priority 1: Priority for express buses on Columbia Pike only
Priority 2: Priority for regular buses on Columbia Pike only
Priority 3: Priority for regular and express buses on Columbia Pike
Priority 4: Priority for cross-street buses only
Priority 5: Priority for all buses

Vehicle Occupancies
Cars: 1.2 persons/vehicle
Buses: 40 passengers/vehicle

Figure 4.15: Impact of Priority on Traffic Performance under INTEGRATION Split-Offset-Cycle Control (AM Peak)

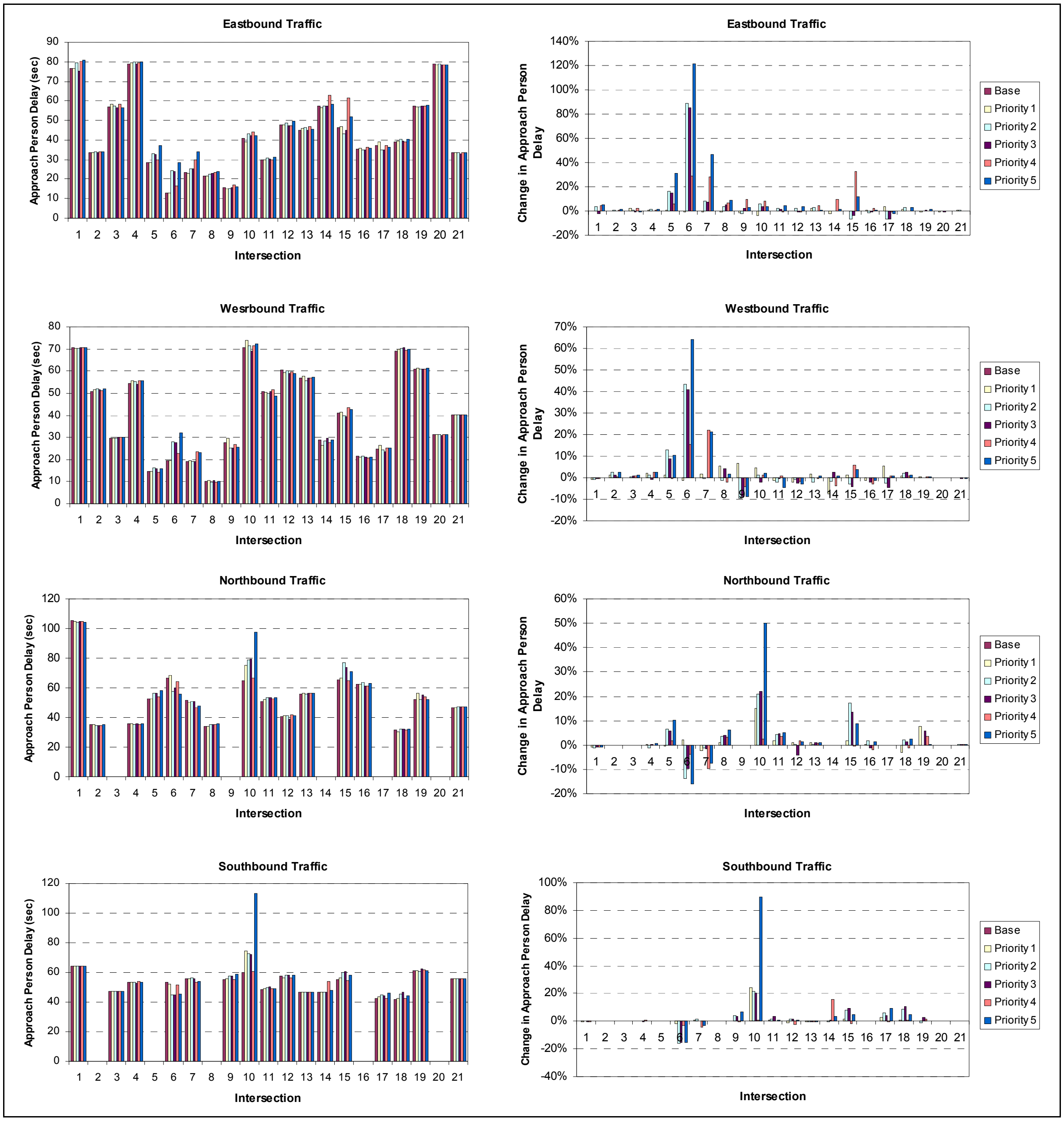


Figure 4.16: Impact of Priority on Approach Delays under INTEGRATION Split-Offset-Cycle Control (AM Peak)

4.2 Midday Analysis Results

This section provides an analysis of the results of the simulations that were conducted to determine the potential benefits of implementing transit priority along Columbia Pike during the Midday period (11:30 a.m. to 1:30 p.m.). Similar to the analysis of the AM peak period results, this section first provides an analysis of the impacts on traffic performance of the various adaptive signal control strategies considered, before following with detailed evaluations of the potential benefits that can be obtained under various signal control strategies from providing priority to transit vehicles.

4.2.1 Impact of Adaptive Signal Control on Corridor

Figure 4.17 and Figure 4.18 illustrate two examples of signal timings generated by the various signal control strategies considered. Figure 4.17 illustrates the timings for the intersection with George Mason, while Figure 4.18 illustrates the timings for the intersection with Glebe. Figure 4.19 and Figure 4.20 complete the presentation of results by illustrating the impact the various signal control strategies have on traffic performance along the corridor. Specifically, Figure 4.19 illustrates the changes in travel time, delay, vehicle stops, fuel consumption and emissions when replacing the fixed-time signal timings of Scenario 1 by each of the alternative adaptive signal control strategies of Scenarios 2 to 6, while Figure 4.20 illustrate the impacts that the alternative controls strategies have on intersection approach delays.

For both intersections, it is observed that the various signal control strategies produced relatively similar signal timing patterns, with a few exceptions:

- The first exception concerns the cycle time. While most of the signal control scenarios feature cycle times of either 75 or 80 seconds, the INTEGRATION Split-Cycle scenario resulted in the implementation of a cycle times of only 40 seconds. This cycle time is about half the cycle time of the other scenarios. This behavior is similar to what was observed in Figure 4.1 for the AM Peak period. Again, such a short cycle was not expected since the fixed-time signals at both ends of the corridor continuously operate with a 75-second cycle throughout the period. The results of Figure 4.17 show that the INTEGRATION signal optimization routines have in this case chosen to "double cycle" the signal operations at the intersections under its control along the corridor. This approach minimizes delay, but also typically increases the number of stops incurred by vehicles, as confirmed by the results of Figure 4.19, where the use of the INTEGRATION Split-Cycle signal control strategy results in an overall decrease in delay of 10.4% and an overall increase in stops of 6.0%.

- At the intersection with George Mason, there is a shift under SCOOT control in the green time allocation from Columbia Pike to George Mason similar to the shift that was observed for the AM Peak period. Under fixed-time control, 61% of the total available green time is allocated to the Columbia Pike leading and main green phases, while the remaining 39% is allocated to the George Mason traffic. Under SCOOT control, this allocation is reversed, with 45% of the green time allocated to the two phases serving Columbia Pike and the remaining 55% now allocated to the George Mason traffic.
- When INTEGRATION is allowed to determine the green splits, the signal timings at the intersection with George Mason are characterized by the implementation of much longer leading green phases on Columbia Pike. As it can be observed in Figure 4.17, this change is essentially implemented at the expense of the Columbia Pike main green. While small reductions are observed in the amount of time allocated to the George Mason green phase, most of the increase in the duration of the Columbia Pike leading green is obtained by reducing the duration of the arterial's main green. For the intersection with Glebe, the balance of green time between both arterials is generally maintained.

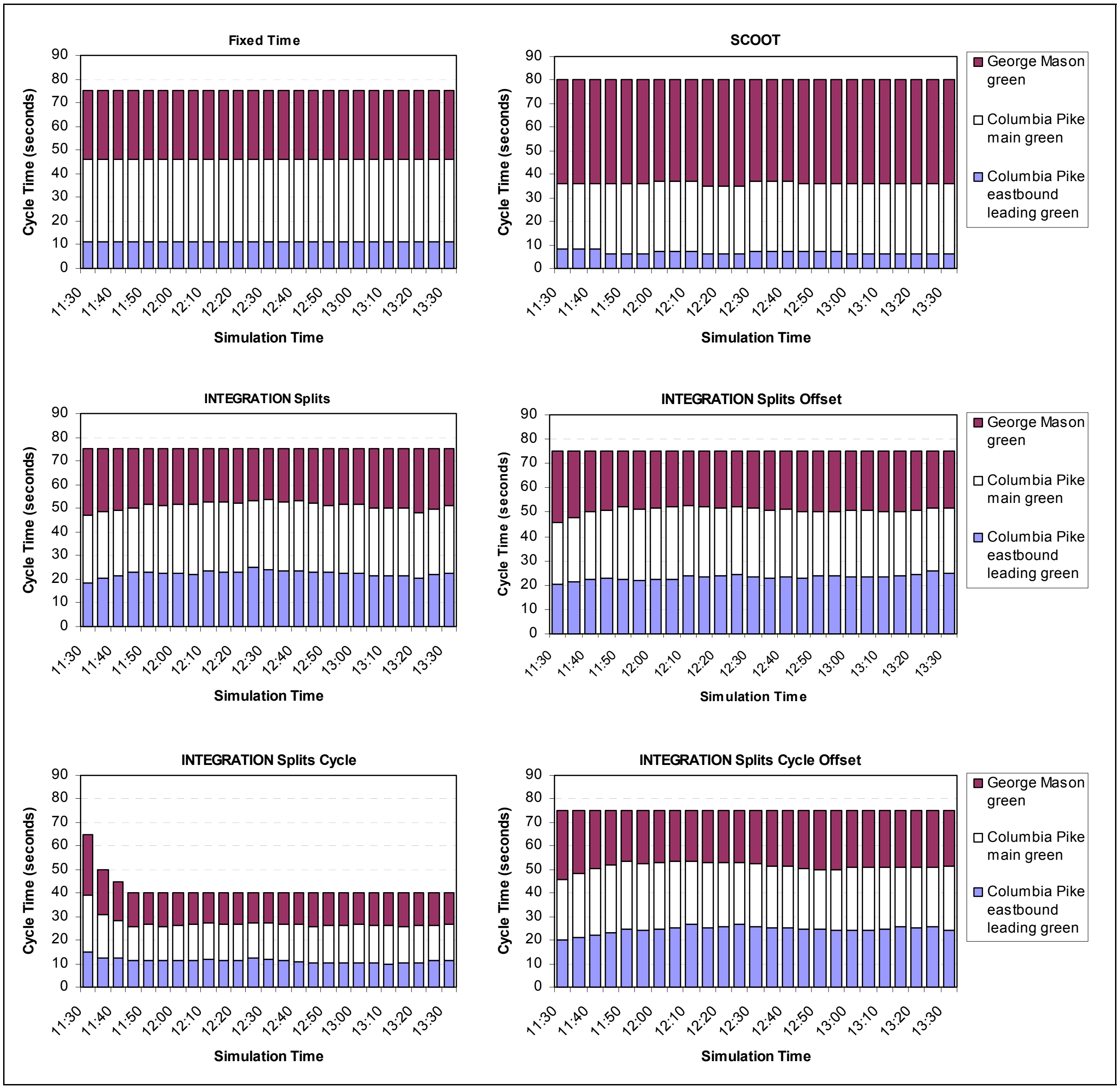


Figure 4.17: Simulated Midday Signal Timing Plans at Intersection with George Mason

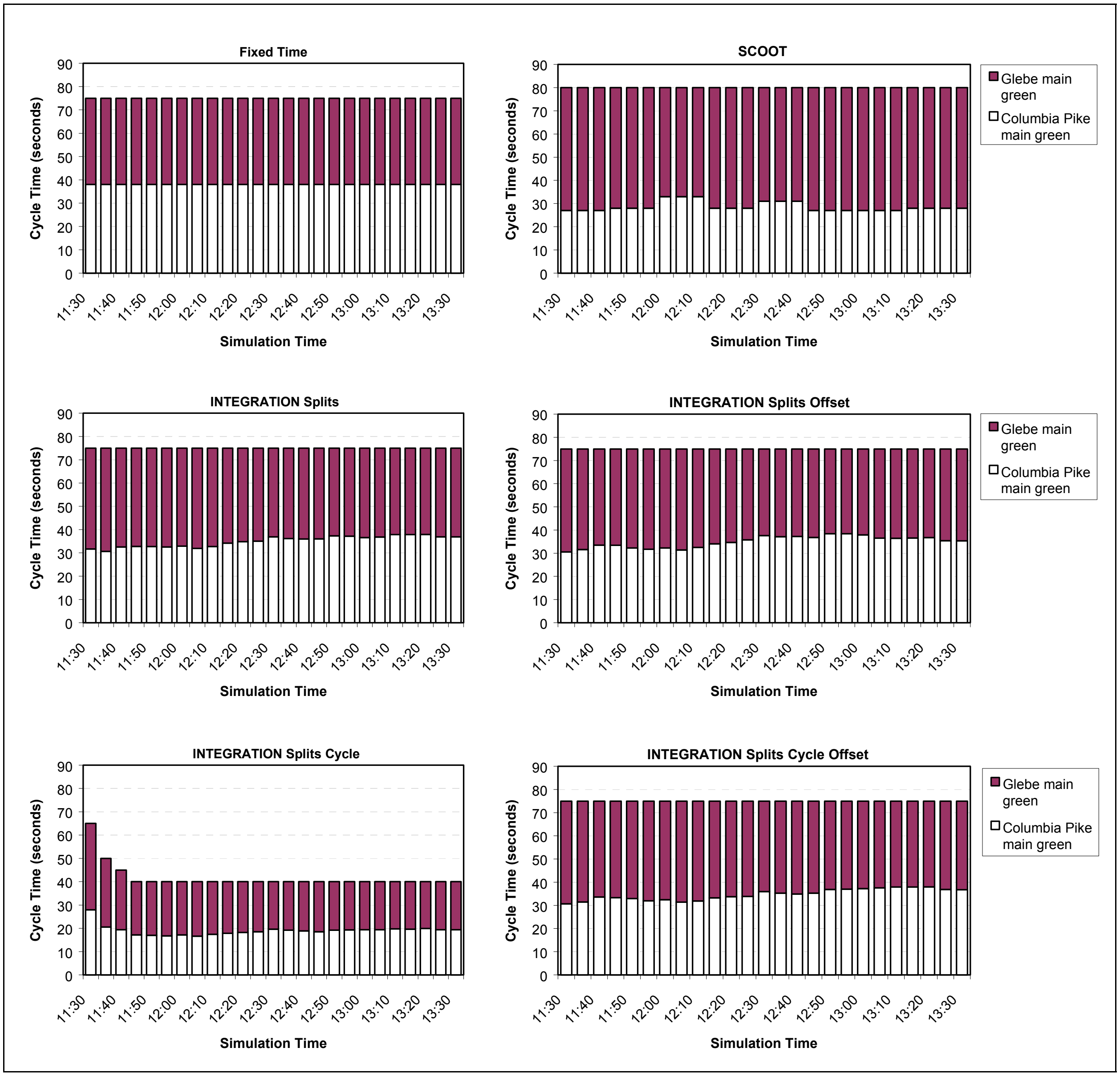
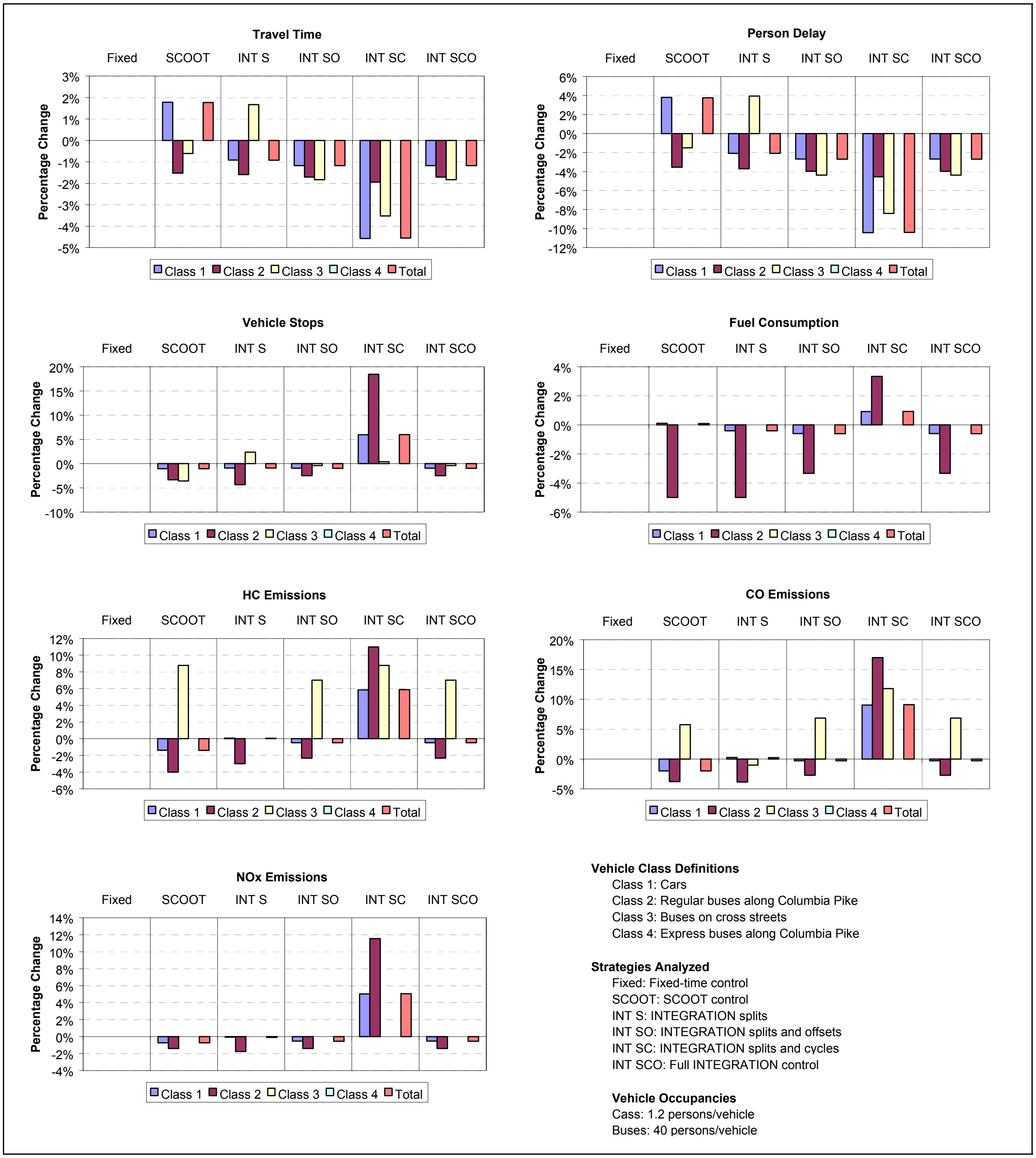


Figure 4.18: Simulated Midday Signal Timing Plans at Intersection with Glebe



Vehicle Class Definitions

Class 1: Cars
Class 2: Regular buses along Columbia Pike
Class 3: Buses on cross streets
Class 4: Express buses along Columbia Pike

Strategies Analyzed

Fixed: Fixed-time control
SCOOT: SCOOT control
INT S: INTEGRATION splits
INT SO: INTEGRATION splits and offsets
INT SC: INTEGRATION splits and cycles
INT SCO: Full INTEGRATION control

Vehicle Occupancies

Cass: 1.2 persons/vehicle
Buses: 40 persons/vehicle

Figure 4.19: Impact of Signal Control Alternatives on Traffic Performance (Midday)

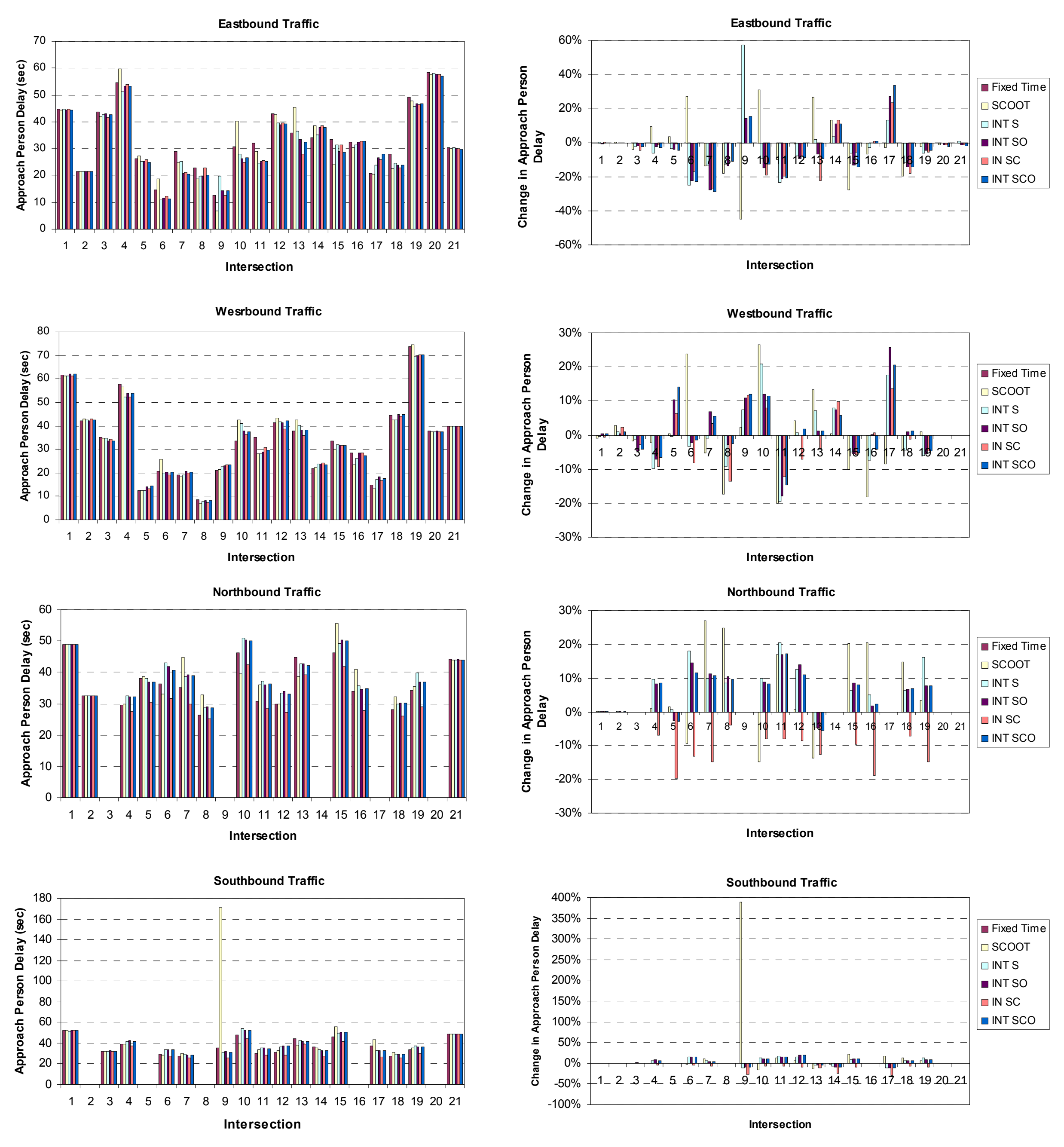


Figure 4.20: Impact of Signal Control Strategies on Intersection Approach Delays (Midday)

When analyzing the results of Figure 4.19, it is observed that the use of adaptive signal control along the study corridor generally results in reduced delays, stops, fuel consumption, and vehicle emissions. The only two scenarios that appear to contradict these conclusions are the SCOOT and INTEGRATION Split-Cycle scenarios:

- In the first case, the simulation results indicate that the SCOOT signal control caused a 3.8% increase in overall delay along the corridor. Similar to the AM Peak period, these results may be explained by differences between the simulated flows and the flows that caused the signal timings coded into INTEGRATION to be implemented along the corridor on June 13 and 14, 2000. The important element here is the fact that the simulated SCOOT timings were modeled as a series of average 15-minute fixed timing plans reflecting the timings that were observed on Columbia Pike on June 13 and 14. Therefore, while the real-world SCOOT system is able to adjust itself to newly detected traffic conditions, the simulated timings are insensitive to changes in simulated demand. Consequently, any difference between the simulated and real-world flows could result in increased stops and delays. Such a difference could then explain the large increase in delay observed in Figure 4.20 for the southbound approach to the intersection with Taylor (Intersection 9) when replacing in the simulation the fixed-timings of Scenario 1 by the observed SCOOT timings of Scenario 2.
- For the INTEGRATION Split-Cycle scenario, the increases in vehicle stops, fuel consumption and emissions are explained by the use of a cycle time that is about half the length of the fixed cycle time used by the intersections at both ends of the corridor. This explanation is identical to the one used to explain the AM Peak period results from scenarios the same signal control strategy.

When comparing the Midday simulation results of Figure 4.19 to the AM Peak results of Figure 4.3, it is observed that the various adaptive signal control strategies considered have a more beneficial impact on overall traffic performance during the Midday period than the AM peak period. While the impacts on fuel consumption and emissions are relatively similar, there are clearly more beneficial impacts on delays and vehicle stops during the Midday period. For the AM Peak period, the implementation of adaptive signal control resulted in overall delay increases in three scenarios, and stop increases in four. For the Midday period, only one scenario result in delay or stop increases. This result was expected. Since there is less traffic demand in the Midday period, there are more opportunities to move the green time from one phase to another to better accommodate observed traffic conditions, and thus, less disrupting opportunities for the general traffic.

Specifically, the application of the INTEGRATION Split timings resulted in a 2.1% decrease in delay for the general traffic and a 0.9% decrease in vehicle stops. Similar decreases were also obtained for the INTEGRATION Split-Offset and Split-Cycle-Offset timings. As was indicated earlier, the delay reduction for the INTEGRATION Split-Cycle scenario reached 10.4%, but at the expense of a 6% increase in stops due to the use of a relatively short cycle. For the SCOOT scenario, the 3.8% delay increase is for its part again attributed to potential inconsistencies between the simulated and actual flows.

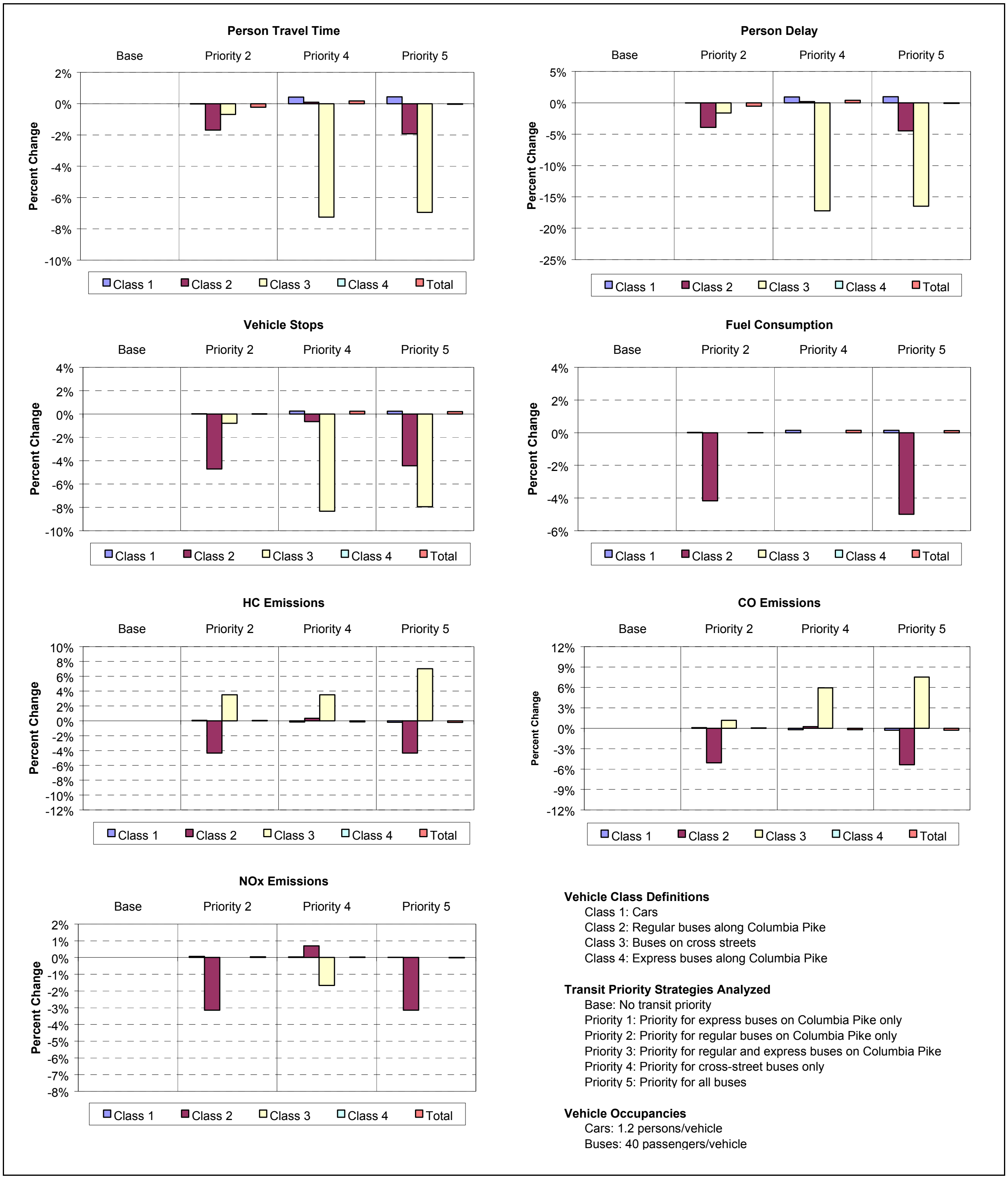
4.2.2 Impact of Alternative Priority Schemes

Figures 4.21 through 4.32 present for the Midday period the performance evaluation of the various transit priority schemes considered for all signal six control scenarios defined in Section 3.4. In this case, the diagrams shown in the various figures only present the results of three priority scenarios, as there are no express buses running along the corridor during the Midday period. Consequently, the Priority 1 scenario (priority only to express buses along Columbia Pike) is in this case identical to the base case (no priority), while the Priority 3 scenario (priority to express and regular buses along Columbia Pike) is identical to the Priority 2 scenario (priority only to regular buses along Columbia Pike).
For the Midday period, the following two general conclusions can be drawn from the analysis of the simulation results:

First, similar to the AM Peak period, Figures 4.21, 4.23, 4.25, 4.27, 4.29 and 4.31 indicate that the prioritized vehicles generally benefit from the priority treatments considered. In this case, delay reductions for the prioritized vehicles ranged from 2.0 to 5.2% when priority is given only to the regular buses along Columbia Pike (Priority 2), and from 9.8 to 22.1% when priority is given to the buses traveling on the cross-streets

(Priority 4). When priority is given to all buses (Priority 5), intermediate delay reductions are obtained. On the other hand, stop reductions range from 1.6 to 8.3% with the Priority 2 scenario, and from 4.3 to 9.3% with the Priority 4 scenario. Reductions in fuel consumption of up to 6.7% are also observed, as well as general reductions in vehicle emissions.

Second, while the prioritized vehicles generally benefit from the various priority schemes considered, the general traffic does not typically benefit from them. In the AM Peak period, the general traffic typically suffered from the various priority schemes considered. In this case, there are no significant positive or negative impacts. In all scenarios considered, delay, stops, fuel consumption and emissions did not change by more than 0.2%. This result is explained by the lower traffic demand and the resulting higher availability of spare green time that can be moved from one phase to another to accommodate approaching transit vehicle without disrupting too much general traffic operations at each intersection. This availability of additional spare green time is particularly reflected in the diagrams of Figures 4.22, 4.24, 4.26, 4.28, 4.30 and 4.32. While the AM Peak simulation result showed delay increases on individual intersection approaches reaching up to 130% and often exceeding 10%, the observed delay increases for the Midday period never exceed 16% and typically remain below 6%.



Vehicle Class Definitions
Class 1: Cars
Class 2: Regular buses along Columbia Pike
Class 3: Buses on cross streets
Class 4: Express buses along Columbia Pike

Transit Priority Strategies Analyzed
Base: No transit priority
Priority 1: Priority for express buses on Columbia Pike only
Priority 2: Priority for regular buses on Columbia Pike only
Priority 3: Priority for regular and express buses on Columbia Pike
Priority 4: Priority for cross-street buses only
Priority 5: Priority for all buses

Vehicle Occupancies
Cars: 1.2 persons/vehicle
Buses: 40 passengers/vehicle

Figure 4.21: Impact of Priority on Traffic Performance under Fixed-Time Control (Midday)

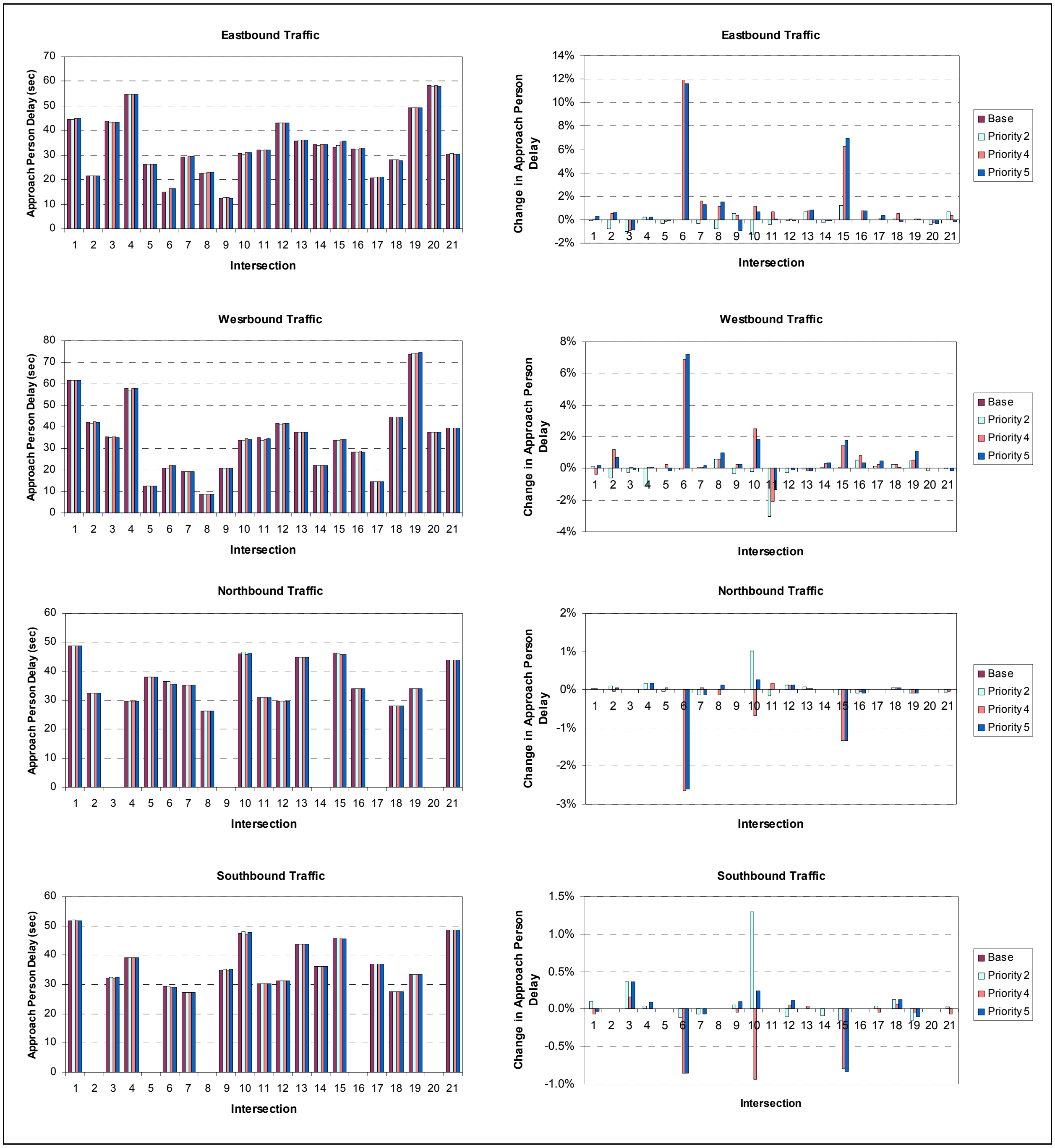
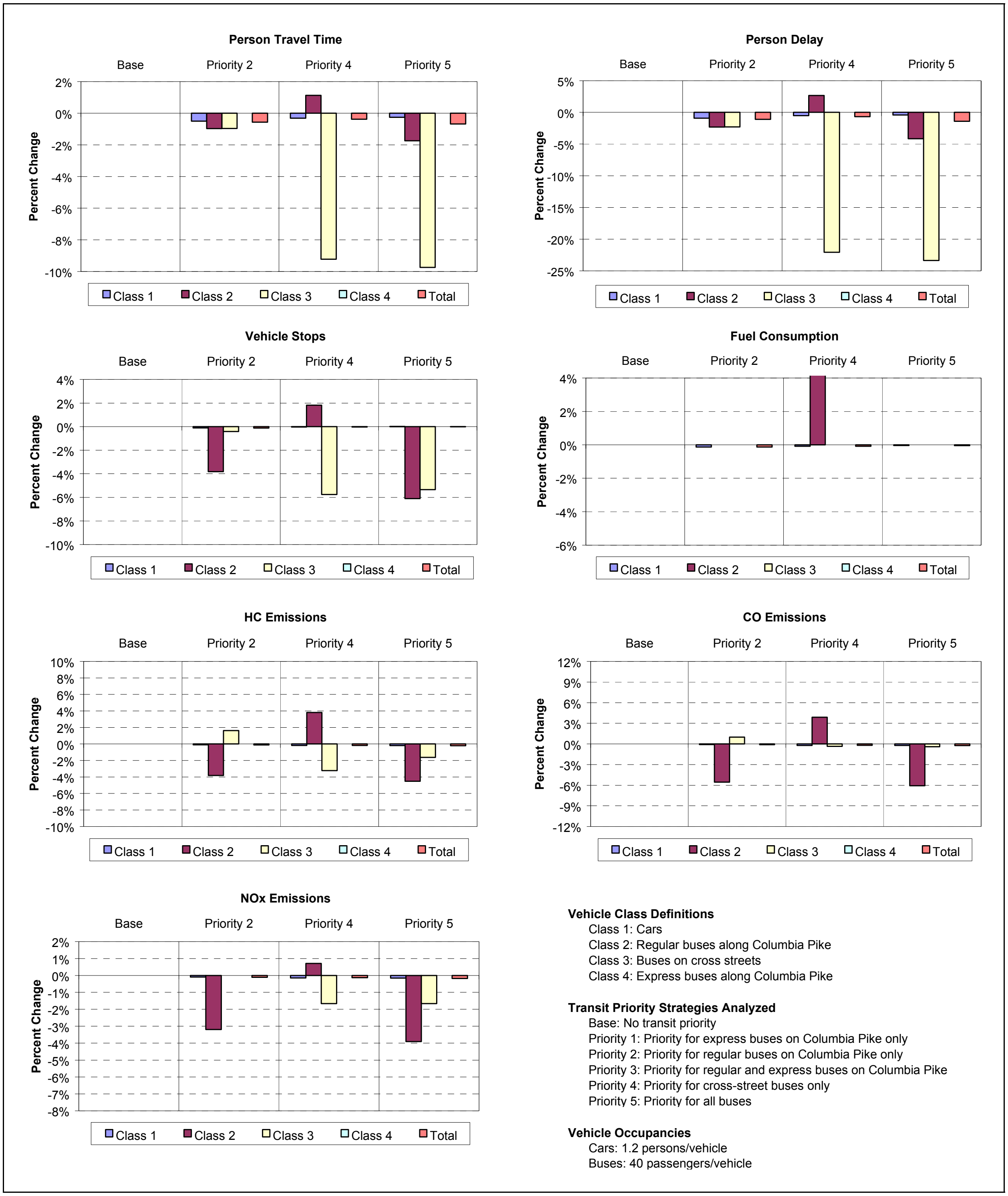


Figure 4.22: Impact of Priority on Approach Delays under Fixed-Time Control (Midday)



Vehicle Class Definitions

Class 1: Cars
Class 2: Regular buses along Columbia Pike
Class 3: Buses on cross streets
Class 4: Express buses along Columbia Pike

Transit Priority Strategies Analyzed

Base: No transit priority
Priority 1: Priority for express buses on Columbia Pike only
Priority 2: Priority for regular buses on Columbia Pike only
Priority 3: Priority for regular and express buses on Columbia Pike
Priority 4: Priority for cross-street buses only
Priority 5: Priority for all buses

Vehicle Occupancies

Cars: 1.2 persons/vehicle
Buses: 40 passengers/vehicle

Figure 4.23: Impact of Priority on Traffic Performance under SCOOT Control (Midday)

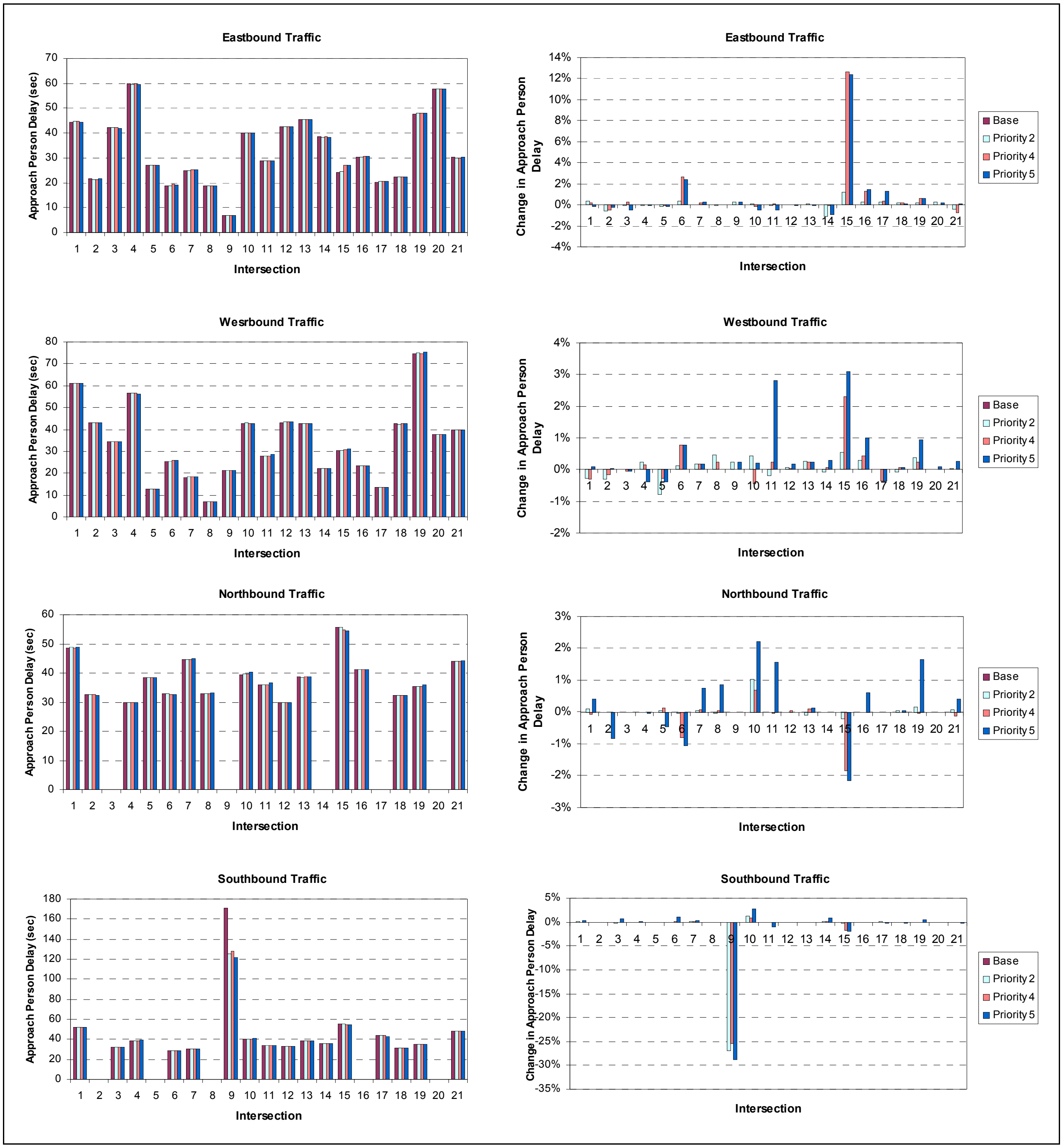
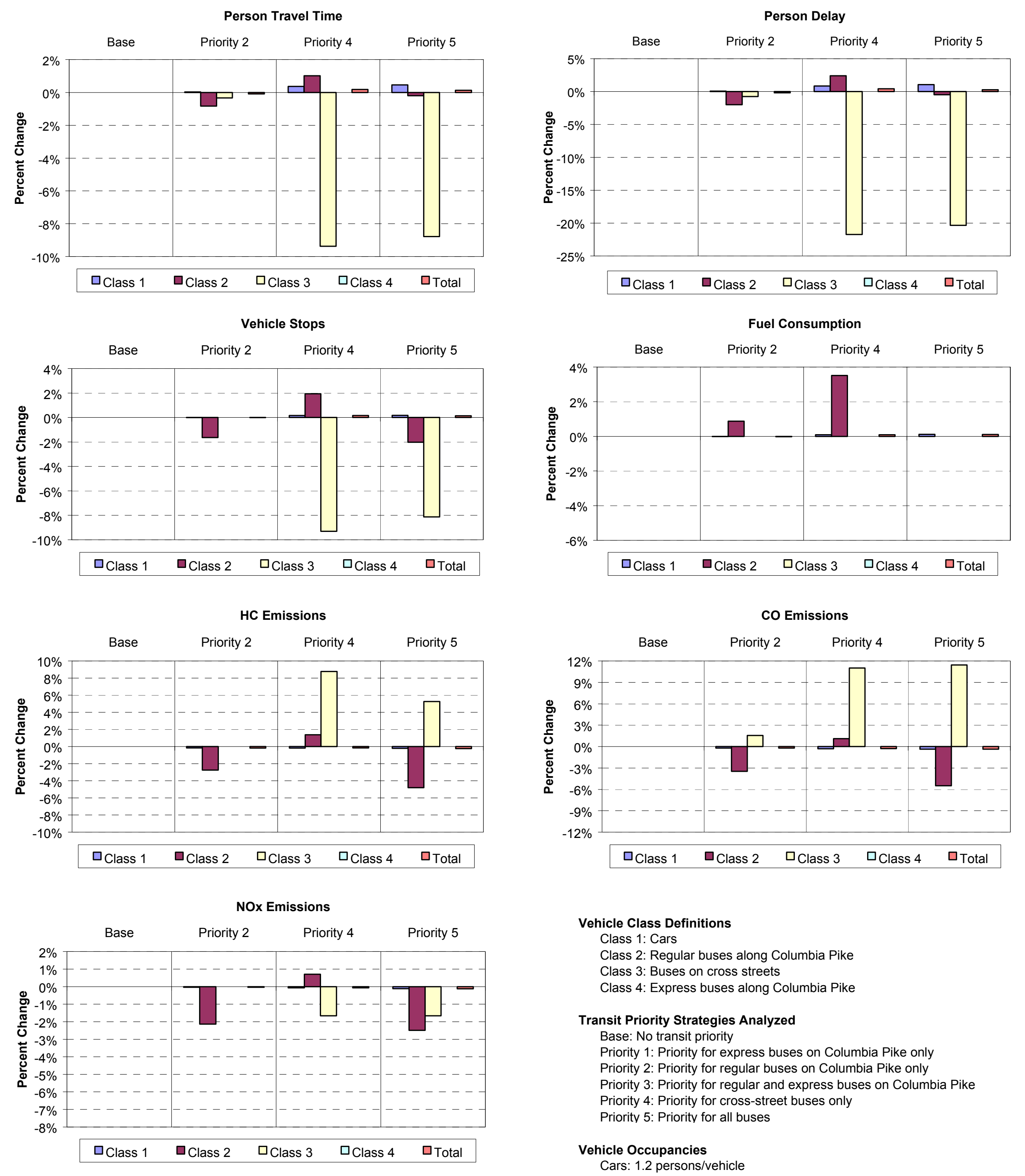


Figure 4.24: Impact of Priority on Approach Delays under SCOOT Control (Midday)



Vehicle Class Definitions
Class 1: Cars
Class 2: Regular buses along Columbia Pike
Class 3: Buses on cross streets
Class 4: Express buses along Columbia Pike

Transit Priority Strategies Analyzed
Base: No transit priority
Priority 1: Priority for express buses on Columbia Pike only
Priority 2: Priority for regular buses on Columbia Pike only
Priority 3: Priority for regular and express buses on Columbia Pike
Priority 4: Priority for cross-street buses only
Priority 5: Priority for all buses

Vehicle Occupancies
Cars: 1.2 persons/vehicle
Buses: 40 passengers/vehicle

Figure 4.25: Impact of Priority on Traffic Performance under INTEGRATION Split Control (Midday)

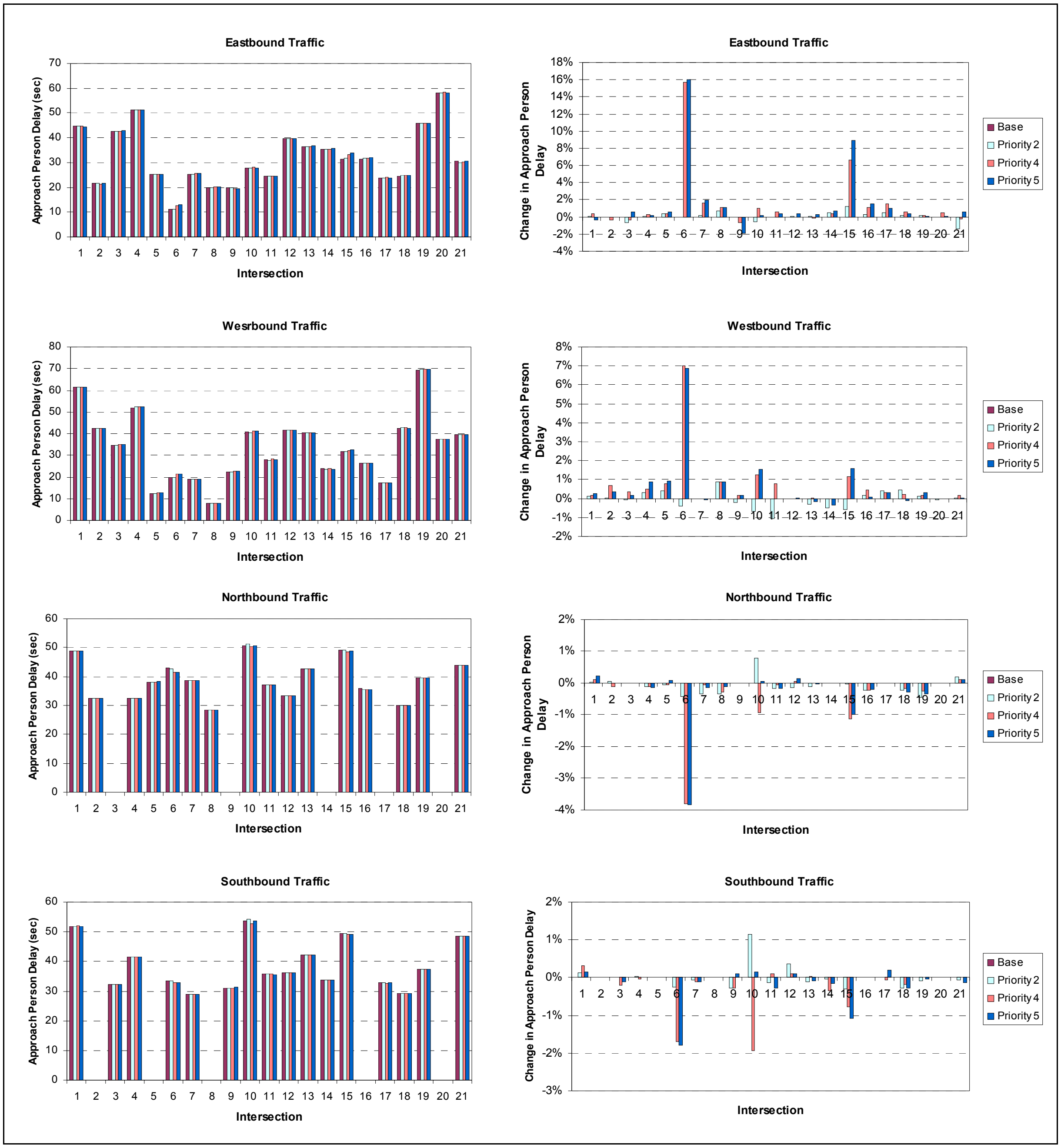
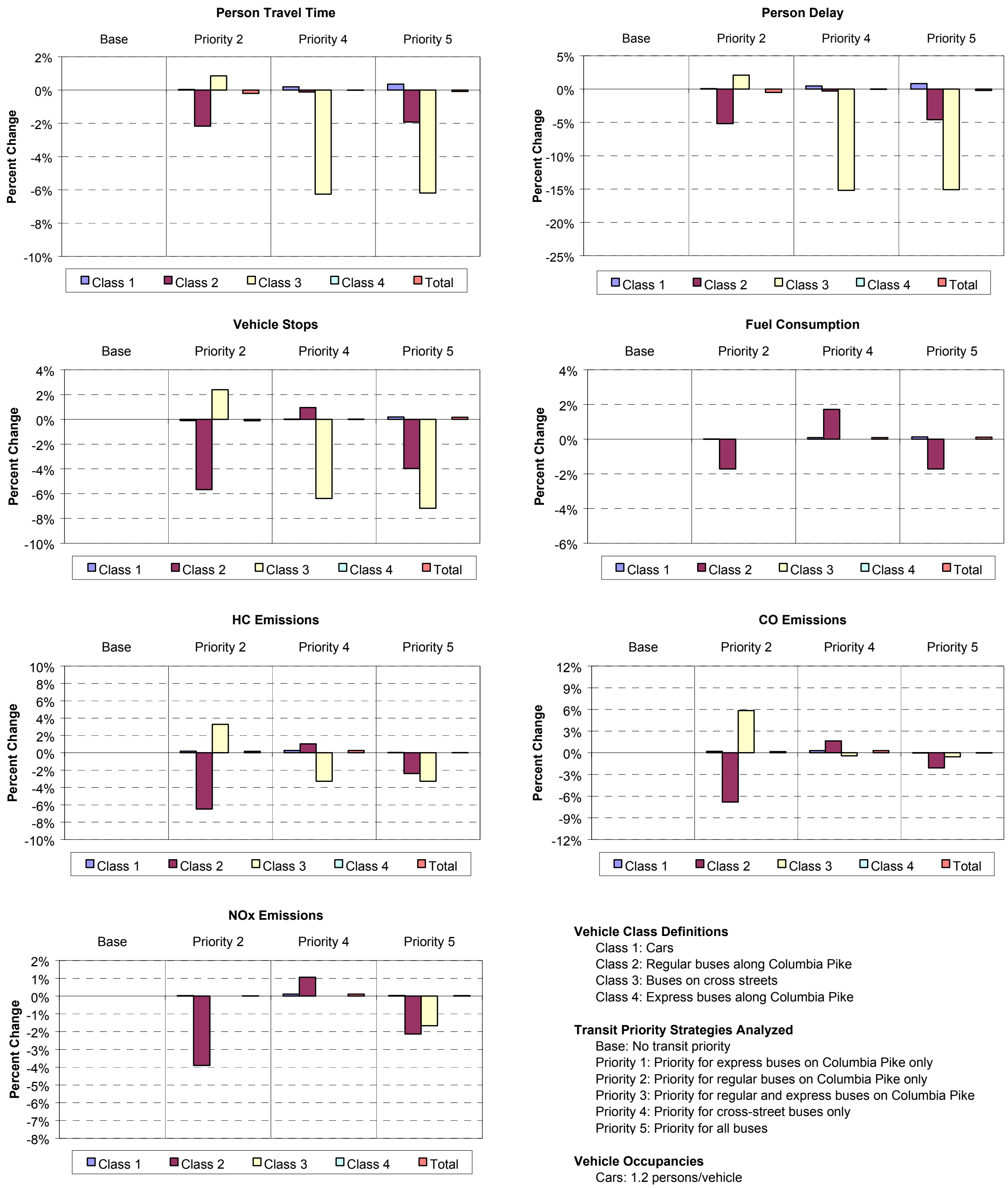


Figure 4.26: Impact of Priority on Approach Delays under INTEGRATION Split Control (Midday)



Vehicle Class Definitions
Class 1: Cars
Class 2: Regular buses along Columbia Pike
Class 3: Buses on cross streets
Class 4: Express buses along Columbia Pike

Transit Priority Strategies Analyzed
Base: No transit priority
Priority 1: Priority for express buses on Columbia Pike only
Priority 2: Priority for regular buses on Columbia Pike only
Priority 3: Priority for regular and express buses on Columbia Pike
Priority 4: Priority for cross-street buses only
Priority 5: Priority for all buses

Vehicle Occupancies
Cars: 1.2 persons/vehicle
Buses: 40 passengers/vehicle

Figure 4.27: Impact of Priority on Traffic Performance under INTEGRATION Split-Offset Control (Midday)

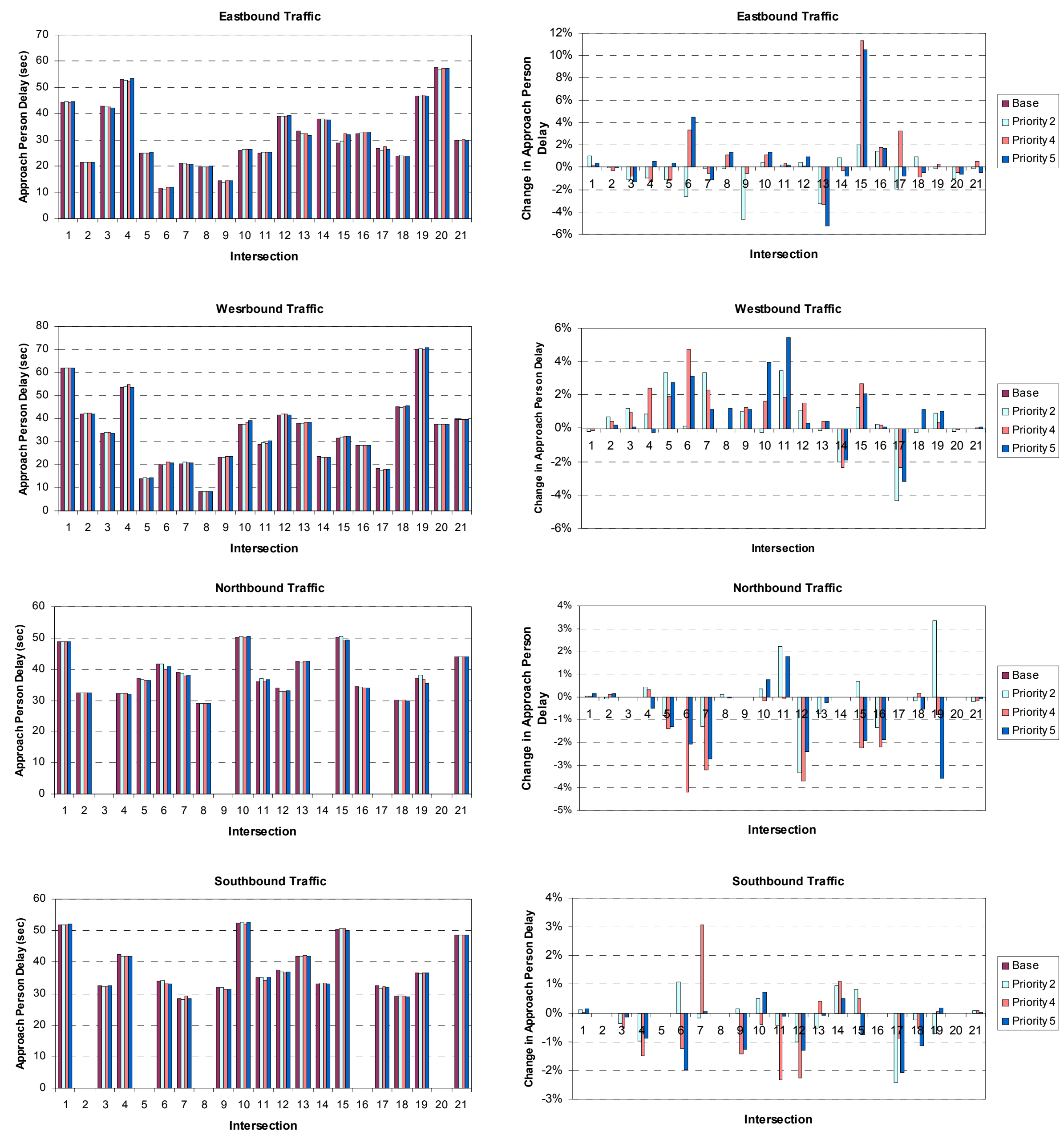
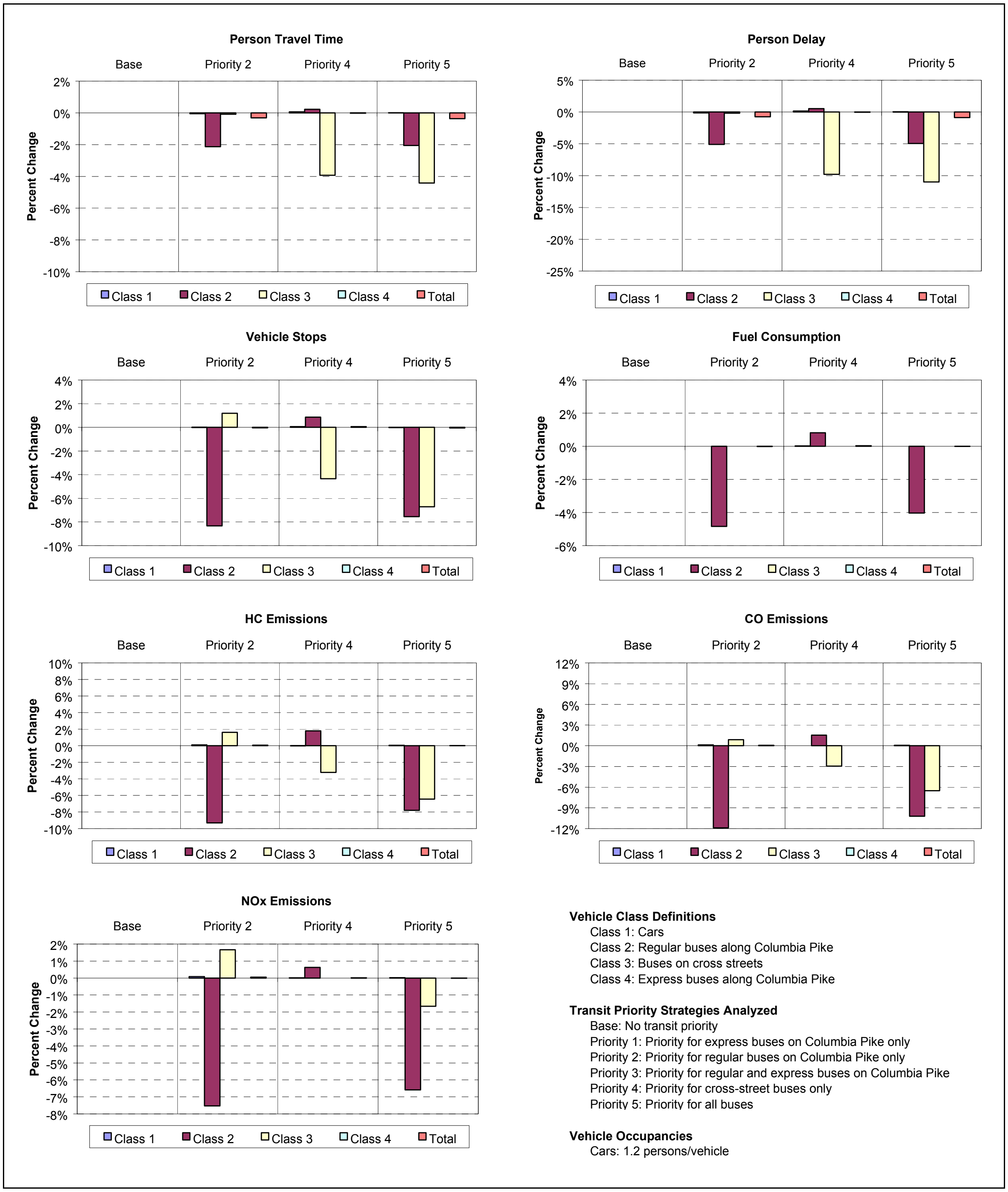


Figure 4.28: Impact of Priority on Approach Delays under INTEGRATION Split-Offset Control (Midday)



Vehicle Class Definitions

Class 1: Cars
Class 2: Regular buses along Columbia Pike
Class 3: Buses on cross streets
Class 4: Express buses along Columbia Pike

Transit Priority Strategies Analyzed

Base: No transit priority
Priority 1: Priority for express buses on Columbia Pike only
Priority 2: Priority for regular buses on Columbia Pike only
Priority 3: Priority for regular and express buses on Columbia Pike
Priority 4: Priority for cross-street buses only
Priority 5: Priority for all buses

Vehicle Occupancies

Cars: 1.2 persons/vehicle

Figure 4.29: Impact of Priority on Traffic Performance under INTEGRATION Split-Cycle Control (Midday)

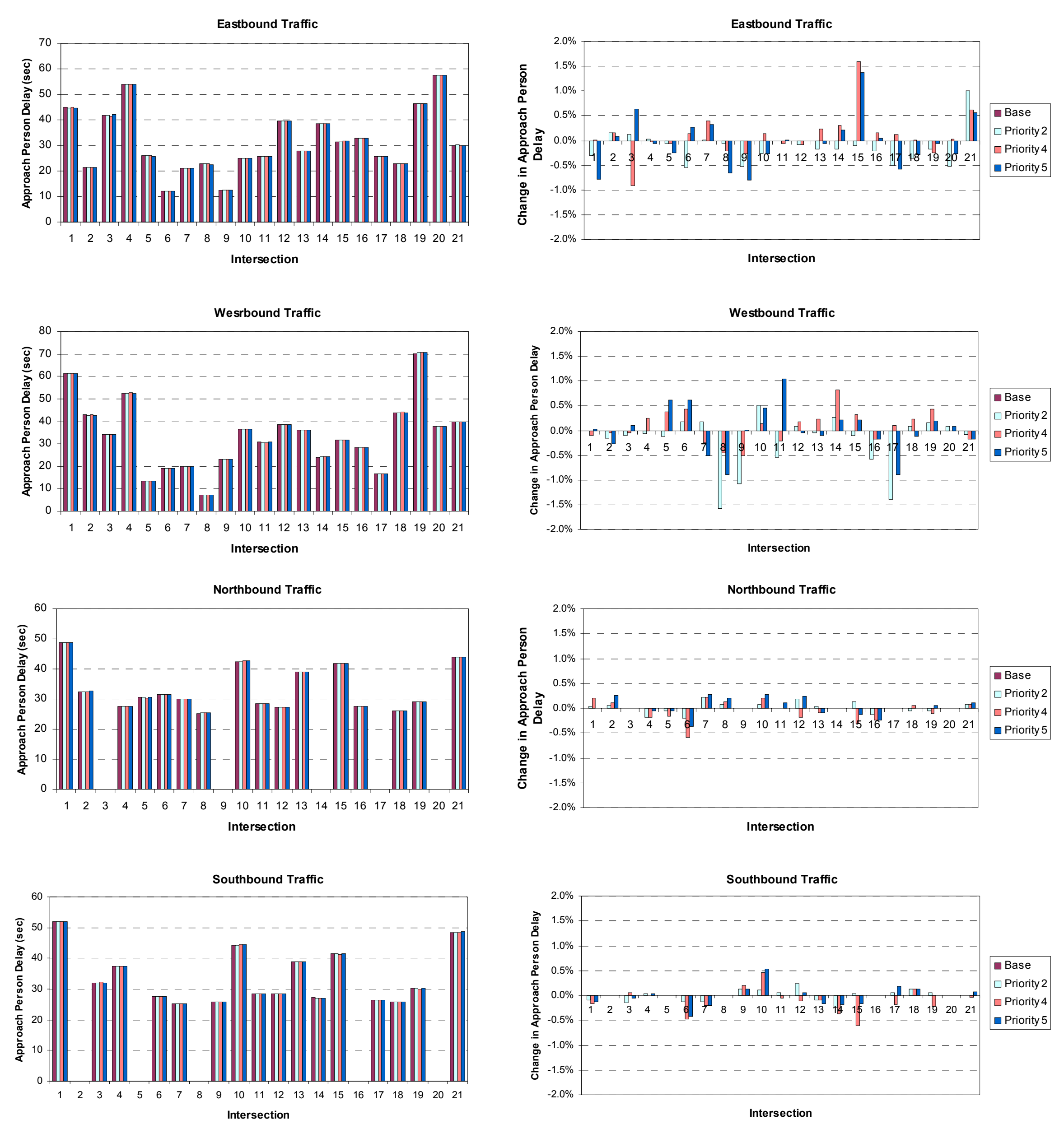
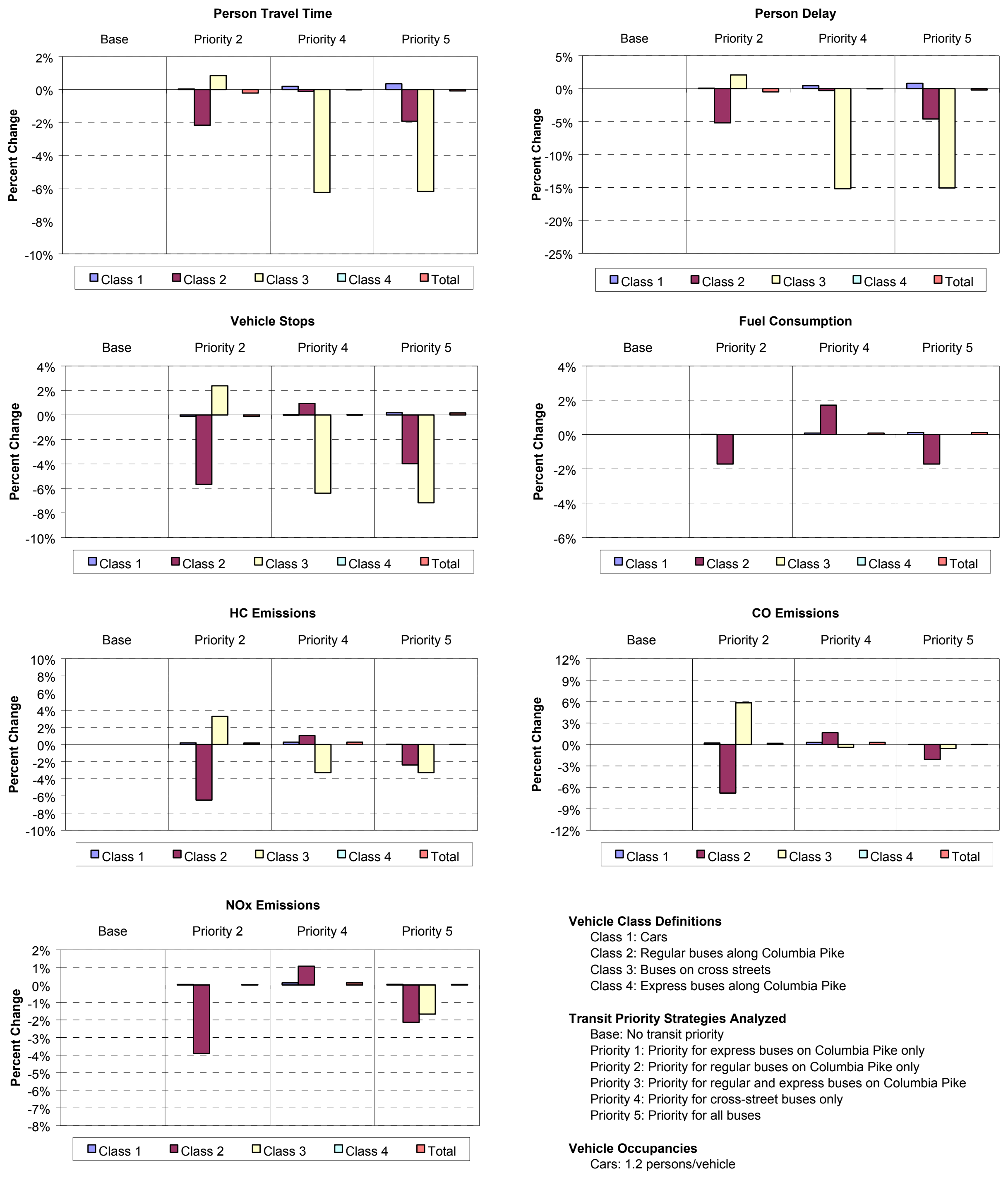


Figure 4.30: Impact of Priority on Approach Delays under INTEGRATION Split-Cycle Control (Midday)



Vehicle Class Definitions
Class 1: Cars
Class 2: Regular buses along Columbia Pike
Class 3: Buses on cross streets
Class 4: Express buses along Columbia Pike

Transit Priority Strategies Analyzed
Base: No transit priority
Priority 1: Priority for express buses on Columbia Pike only
Priority 2: Priority for regular buses on Columbia Pike only
Priority 3: Priority for regular and express buses on Columbia Pike
Priority 4: Priority for cross-street buses only
Priority 5: Priority for all buses

Vehicle Occupancies
Cars: 1.2 persons/vehicle

Figure 4.31: Impact of Priority on Traffic Performance under INTEGRATION Split-Offset-Cycle Control (Midday)

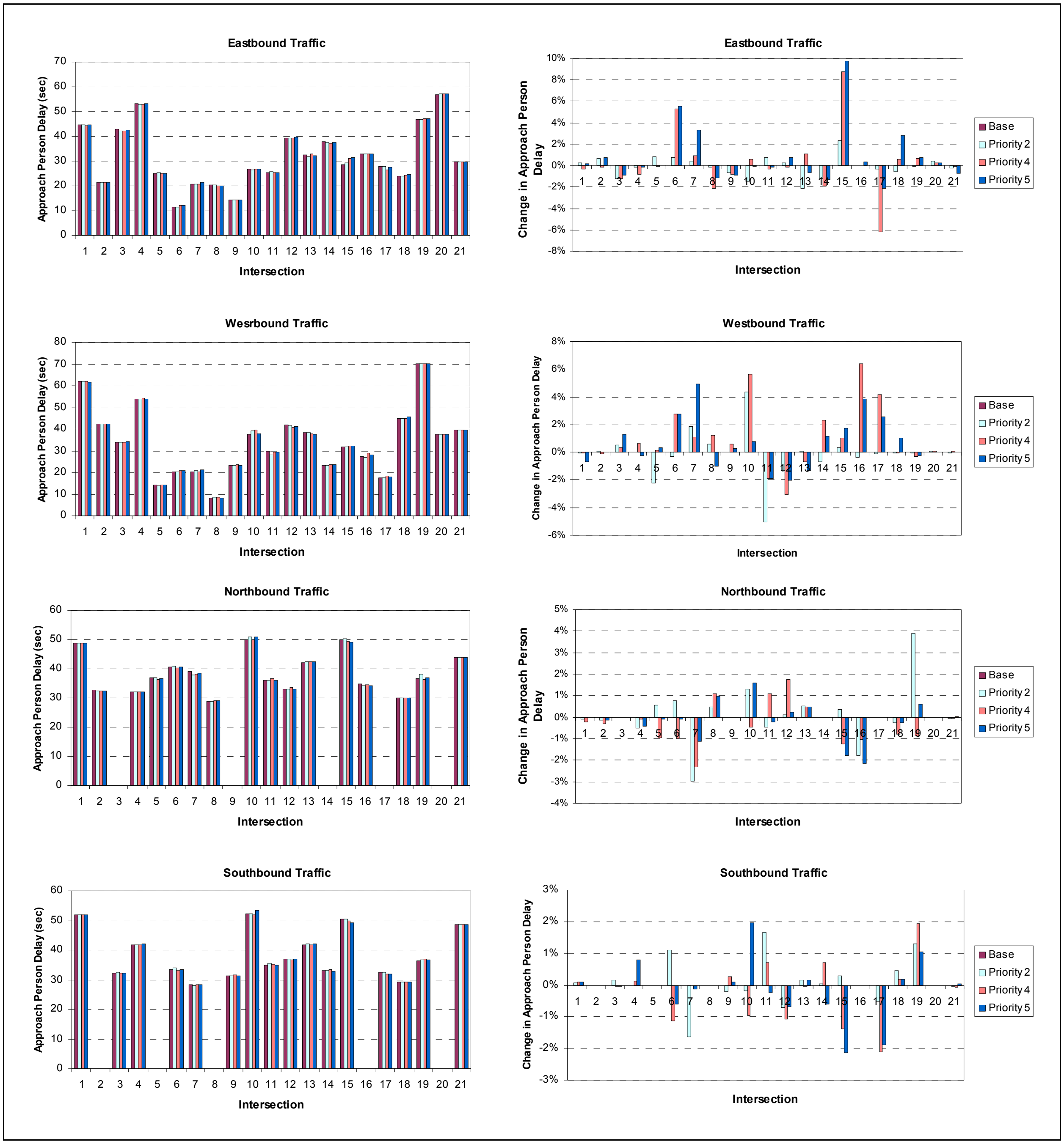


Figure 4.32: Impact of Priority on Approach Delays under INTEGRATION Split-Offset-Cycle Control (Midday)

4.3 Conclusions and Recommendations

This chapter described findings of a simulation study that was conducted to assist the Washington D.C. ITS Task Force in considering the implementation of signal preemption and other vehicle priority strategies along signalized arterials in the Washington D.C. metropolitan area.

Within the study, the impact of the five following transit priority strategies on the AM peak and Midday traffic were considered under alternative signal control scenarios simulating the actual MONARC fixed-time plans, observed SCOOT system signal timings, and adaptive signal timings determined by the INTEGRATION signal timing optimization routines:

- **Base Scenario:** No priority offered to any vehicle.
- **Priority Scenario 1:** Priority only to express buses traveling along Columbia Pike.
- **Priority Scenario 2:** Priority only to regular buses traveling along Columbia Pike.
- **Priority Scenario 3:** Priority to all buses traveling along Columbia Pike only.
- **Priority Scenario 4:** Priority to buses traveling on streets crossing Columbia Pike.
- **Priority Scenario 5:** Priority to all buses traveling along Columbia Pike and its cross-streets.

In each scenario, a simple priority scheme was considered. First, approaching transit vehicles were detected within the simulation model when they arrived within 100 m of a signalized intersection. Following this detection, the transit priority logic then provided either a green extension or an early green recall to accommodate the approaching vehicle. Both the green extensions and early green recalls were determined using increments of 5 seconds and with the constraint to maintain the cycle time. Some minimum and maximum green interval constraints for each signal phase were also taken into consideration to avoid providing too large extensions or early recalls.

Before indicating the general conclusions of the study, it should be pointed out that the results of this study should not be viewed as definite, but rather as a general assessment of the potential benefits of implementing transit priority along the Columbia Pike corridor. In particular, it must be considered that the results of the study are subject to the limitations of the simulation model used to conduct the evaluation. In this study, while an effort has been done to include as many significant factors as possible, it was not possible to consider all elements that could affect the benefits of providing priority of passage to transit vehicles along the corridor. For instance, simple priority logic was considered in the simulation study. More complex logic providing conditional priority based on the occupancy of vehicles requesting priority of passage, the level of congestion at the signalized intersection and the degree to which the prioritized vehicle is ahead or behind schedule could not be considered. The study further assumed that all buses stopped at all transit stops along the corridor, while in reality buses would not always do so.

When evaluating adaptive control with SCOOT, it must further be pointed out that the evaluations were made with an approximate representation of the capabilities of the SCOOT system used along Columbia Pike. While observed SCOOT timings were simulated, these timings were averaged over 15-minute intervals. In reality, the SCOOT system allows signal changes to occur every cycle. In addition, there was no certainty that the simulated flows truly matched the flows that caused the observed timings. Because of the adaptive nature of the SCOOT system, such an evaluation can only be done through a field study or through a detailed modeling of the arterial control using corresponding signal and traffic data collected on the same day.

The results of the simulations first indicate that it is generally difficult for adaptive signal control to improve on optimum fixed-time signal control, especially when the signals are controlling relatively constant or for congested traffic demands. The strength of adaptive control is its ability to adjust to observed changes in traffic conditions. When there are only a few changes, a fixed-time operation may already operate near optimum. When congestion appears, there is an increased pressure to use the maximum allowable green time allocated to each phase, which would then create a virtual fixed-time operation. In both situations, adaptive control can still provide some benefits by being able to react to some cycle-to-cycle fluctuations, but the benefits would be marginal.

Regarding transit priority, the results of the simulation study for both the AM Peak and Midday travel periods indicate that the prioritized vehicles usually benefit from any priority scheme considered. During the AM Peak period, the simulations clearly indicate that these benefits are typically obtained at the expense of the general traffic. While buses experience reductions in delay, stops, fuel consumption, and emissions, the opposite typically occurs for the general traffic. Furthermore, since there are significantly more cars than buses along the corridor, the negative impacts experienced by the general traffic during this period outweigh in most cases the benefits to the transit vehicles, thus yielding overall negative impacts for the various priority schemes considered. For the Midday period, there are no apparent impacts, as there is then more spare capacity to accommodate approaching transit vehicles at signalized intersections without significantly disrupting traffic operations.

For the AM Peak period, the simulation results further indicate that overall benefits could be obtained if the number of prioritized vehicles is kept low. In this case, overall benefits were for instance obtained only in scenarios in which priority was given exclusively to the express buses traveling along Columbia Pike. These scenarios featured very few prioritized passages in comparison to the other scenarios. Conversely, the worse scenarios in terms of overall benefits were typically obtained when priority was provided to all buses.

The simulation results finally indicate that overall benefits could be obtained when priority is awarded within a system using non-optimal signal timings. In such case, benefits can be obtained when the green time that is added to accommodate an approaching transit vehicle increases the total green time allocated to an approach with initially less than optimal green time.

5 SYSTEMATIC EVALUATION OF TRANSIT SIGNAL PRIORITY IMPACTS AT ISOLATED SIGNALIZED INTERSECTIONS

5.1 Introduction

Chapter 3 and 4 presented the results of a field and simulation evaluation of transit signal priority and adaptive signal control along Columbia Pike. While the study did provide significant contributions to the understanding of transit signal priority and adaptive signal control, it also raised several questions regarding the sensitivity of the results to a number of factors. Unfortunately, while the analysis involved a real-life case study, it was conducted on a fairly large network deeming it extremely difficult to identify critical traffic, transit, and signal-timing factors that impact the benefits of a transit signal priority system. Consequently, the objective of this chapter is to attempt to address these questions through a systematic evaluation of transit signal priority at an isolated signalized intersection.

5.1.1 Objectives of Research

The objective of this research effort is to isolate the impacts of various traffic, transit, and signal timing factors on the potential benefits of transit signal priority. This objective is achieved by conducting a systematic analysis of transit signal priority at an isolated intersection. The use of such a simple network to conduct the study is required in order to isolate the impacts of various factors.

5.1.2 Significance of Research

The significance of this research effort lies in the fact that it not only quantifies the potential benefits of transit signal priority for both transit vehicles and the general traffic, but it systematically identifies the critical factors that impact the benefits of transit signal priority.

5.1.3 Chapter Layout

Clearly the benefits of transit signal priority are impacted by the logic that is utilized to provide priority to the transit vehicles. Consequently, the priority logic that is embedded in the INTEGRATION microscopic simulation model is described in detail. Subsequently, the test network and test scenarios that were evaluated are described followed by an analysis of the simulation results. Several factors are considered in the study, including the effect of traffic demand, transit vehicle demand, demand distribution at the signalized approaches, the phasing scheme, the effect of the optimality of the base signal timing plan, and the dwell time at a near-side bus stop are considered. Finally, the findings and conclusions of the study are presented and recommendations for further research are presented.

5.2 Background

Prior to describing the test network and scenarios that were considered for the evaluation of transit priority, a brief description of the transit priority logic that is currently embedded in the INTEGRATION 2.30d model is described.

The transit signal priority logic that is embedded in the INTEGRATION 2.3d model detects transit vehicles that are within 100 m of the traffic signal to provide either a green extension or an early green recall to accommodate the approaching transit vehicle, subject to the need to maintain a common network cycle length, as summarized in Figure 5.1. The logic of Figure 5.1 is used within the INTEGRATION software to determine whether signal changes are required at an intersection to accommodate an approaching transit vehicle. The operation of this logic is best described through an example. In Figure 5.1, if it is assumed that the traffic signals A and B operate on a two-phase mode with a common cycle length, the detection of a transit vehicle traveling eastbound while traffic on the east/west travel direction is being served may result in a number of possible outcomes depending on when the detected transit vehicle is projected to arrive at intersection A within the signal cycle:

- If the transit vehicle is projected to arrive early in the green interval so that it can proceed uninterrupted through the intersection, no alterations are made to the signal timings.
- Alternatively, if the transit vehicle is projected to arrive after the end of the green interval, the interval is extended at increments of 5 seconds until the transit vehicle is served or the maximum green interval duration has been reached. Currently the maximum green interval is set to equal the cycle length, minus the summation of the intergreen times of all the phases defined in the signal cycle and the summation of a 5-second minimum green for each phase defined within the signal cycle. It should be noted that the transit priority logic is checked each second to identify what changes if any should be made to the signal timings.
- If, on the other hand, the traffic signal at intersection A serves the north/south approaches as the transit vehicle arrives, the priority logic truncates the north/south phase after providing the required amber interval.
- Finally, if transit vehicles are detected on two conflicting approaches, as illustrated in Figure 5.3, the transit signal priority logic makes no changes to the signal timings as the priority calls from both approaches are equally weighed.

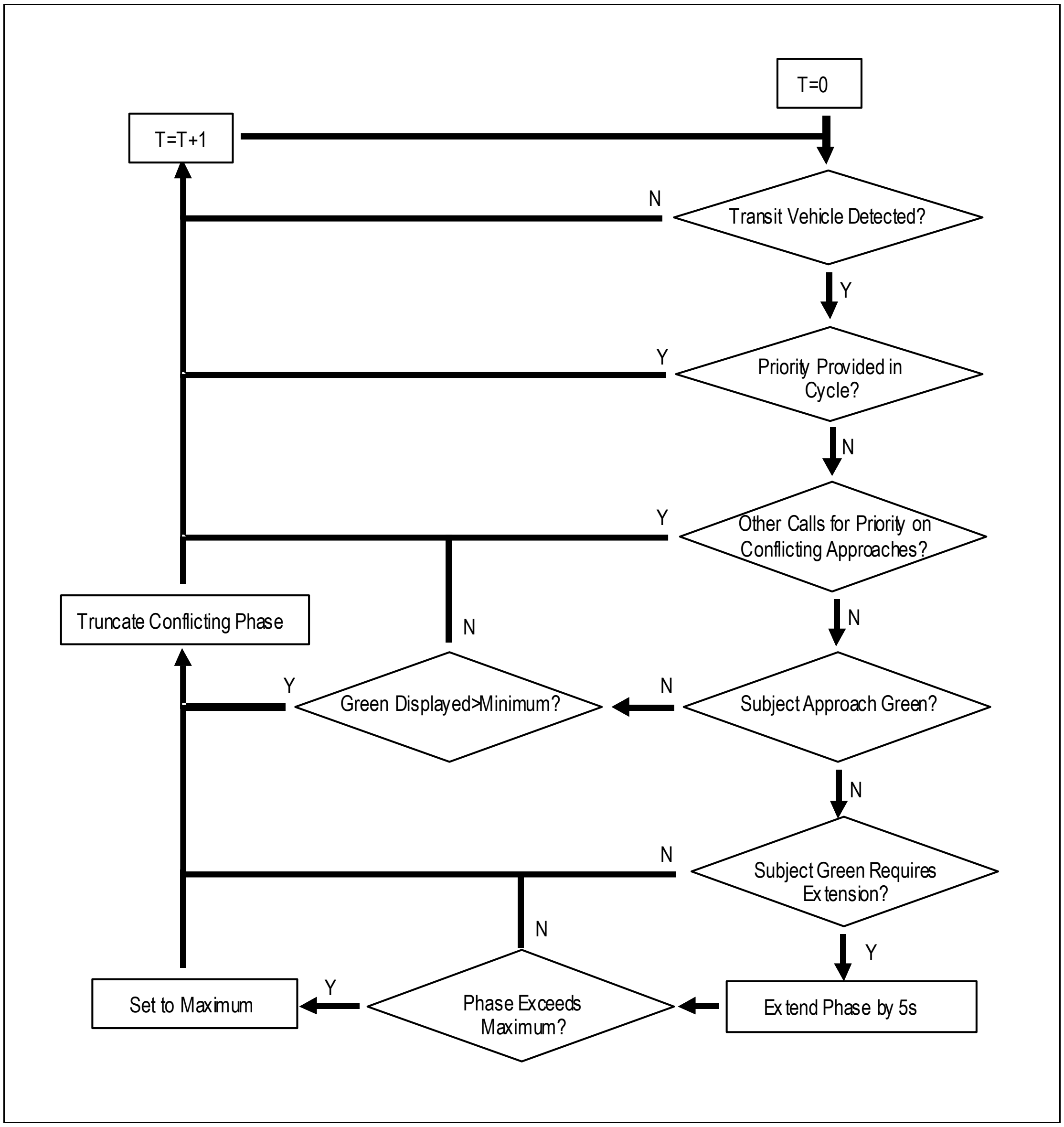
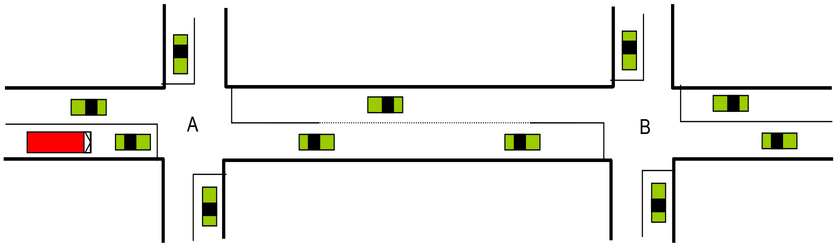


Figure 5.1: Flow Chart of INTEGRATION Transit Priority Logic

a. Transit vehicle arrival in single direction



b. Transit vehicle arrival in multiple directions

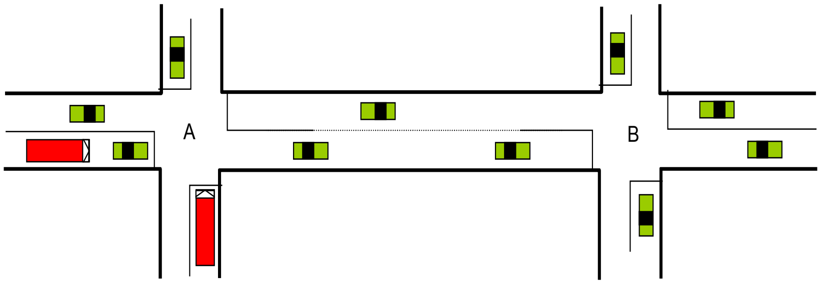


Figure 5.2: Example of Transit Signal Priority with calls from Eastbound and Northbound Approaches

Enhancements to the INTEGRATION transit priority logic are being incorporated in order to provide priority that is weighed by the occupancy of the transit vehicles. Further enhancements to the logic will include the capability of altering the distance upstream the traffic signal where the bus is detected, the minimum green time, the maximum green time, and the green extension parameters. Finally, the enhanced logic will also consider the level of congestion on conflicting approaches in such a way that priority would only be provided to approaching transit vehicles when traffic conditions around a signalized intersection permit signal alterations to be implemented without generating undue congestion.

5.3 Test Network and Scenario Description

This section describes the test network and test scenarios that were considered in the analysis prior to discussing the study results in the subsequent section.

5.3.1 Test Network Description

The test network that was analyzed consisted of four approaches to a signalized intersection, as illustrated in Figure 5.3. Two traffic signal phasing schemes were considered in the analysis, namely, a two-phase and a four-phase scheme. For the base two-phase scheme an equal demand of 600 veh/h was loaded in the eastbound and northbound directions, respectively. Alternatively, for the base four-phase scheme an equal demand of 254 veh/h was loaded on all approaches to the signalized intersection in order to maintain the same volume-to-capacity ratio for both phasing schemes.

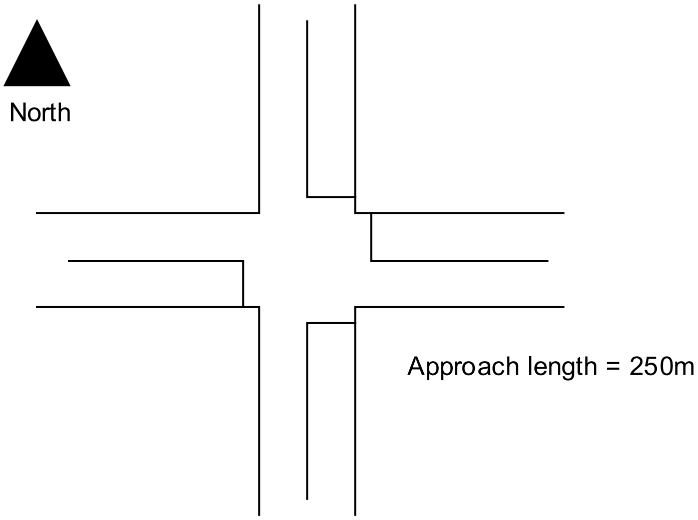
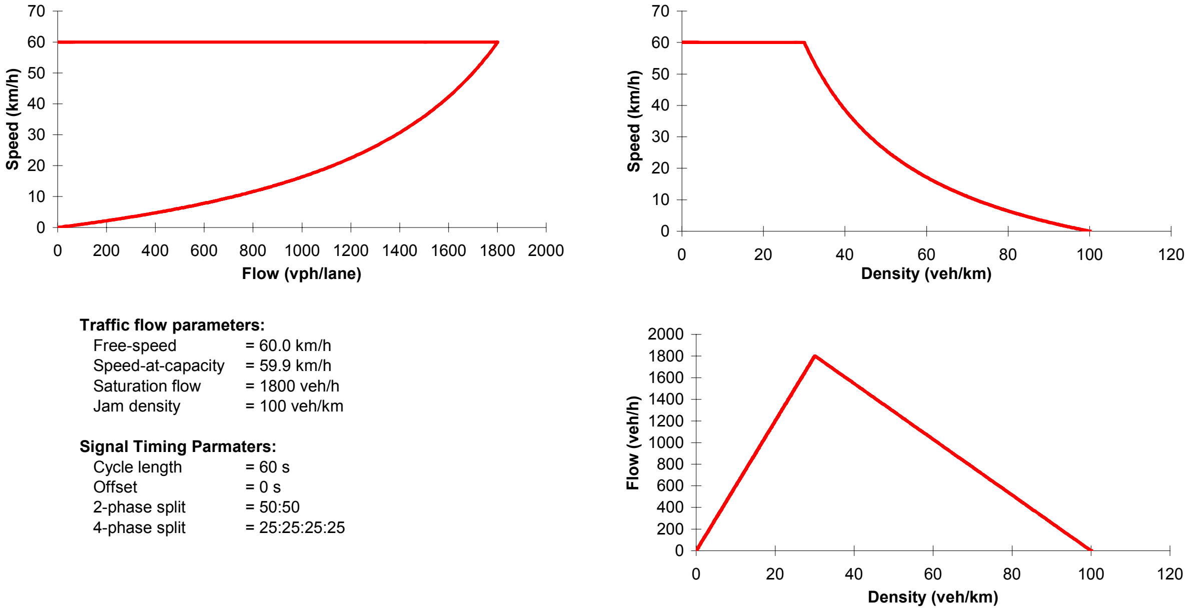


Figure 5.3: Test Network Configuration

An optimum cycle length of 60 seconds with a 50:50 phase split for the two-phase scheme and a 25:25:25:25 phase split for the four-phase scheme was implemented. The traffic signal offset was set at 0 seconds and the demand was loaded for a total of 5 minutes with an additional 15 minutes to clear the network of any vehicles traveling along the network.

In order to ensure that increases in vehicle delay were only caused by the traffic signal operations as opposed to differences in traffic demand, the speed-at-capacity was set approximately equal to the free-speed (59.9 and 60.0 km/h, respectively), as illustrated in Figure 5.4. The unopposed saturation flow rate was set at 1800 veh/h, which corresponds to a queue discharge headway of 2 seconds. The jam density of 100 veh/km results in a vehicle spacing of 10 meters when vehicles are full stopped.



Traffic flow parameters:
Free-speed = 60.0 km/h
Speed-at-capacity = 59.9 km/h
Saturation flow = 1800 veh/h
Jam density = 100 veh/km

Signal Timing Parmaters:
Cycle length = 60 s
Offset = 0 s
2-phase split = 50:50
4-phase split = 25:25:25:25

Figure 5.4: Speed/Flow/Density Relationships for Signalised Approaches

5.3.2 Test Scenario Description

In order to provide a systematic evaluation of transit signal priority, a sensitivity analysis was conducted using a number of variables, as summarized in Table 5.1. A total of 9 variables were considered in the study that included the time of departure of a transit vehicle, the signal phasing scheme, the total traffic demand approaching the intersection, the demand distribution across various approaches, the signal cycle length, the signal phase split, the approach on which the transit vehicle arrived, the dwell time at the bus stop, and the frequency of buses.

Table 5.1: Scenario Experimental Design

Variable	Variable Description	Number of Levels	Level Description
A	Bus departure time	8	0.0, 7.5, 15.0, 22.5, 30.0, 37.5, 45.0, and 52.5
B	Phase scheme	2	2-phase and 4-phase
C	Total traffic demand	5	800, 1000, 1200, 1400, and 1600 veh/h
D	Demand distribution	11	100/1100, 200/1000, 300/900, 400/800, 500/700, 600/600, 700/500, 800/400, 900/300, 1000/200, and 1100/100
E	Cycle length	3	40, 60, and 80 seconds
F	Phase split	5	30/70, 40/60, 50/50, 60/40, and 70/30
G	Bus approach	2	Eastbound and northbound
H	Bus stop duration	5	5, 10, 15, 30, and 60 seconds
I	Bus frequency	3	12(every 5 minutes), 36 (every1.67 minutes), and 60 buses/h (every minute)

Eight transit vehicle departure times (variable A) were considered in order to isolate the impact of transit vehicle arrival time at the signalized intersection on the potential benefits of transit signal priority. In addition, overall average benefits were estimated by averaging over the eight potential transit vehicle arrival times.

Given that the logic that is embedded in INTEGRATION 2.3d provides transit priority while maintaining a common cycle length, it was important to investigate the sensitivity of the results to the number of signalized phases. Consequently, two phasing schemes were considered: a 2-phase scheme and a 4-phase scheme (variable B). As was mentioned earlier, in both schemes the volume-to-capacity ratio was held constant at the signalized approaches. For example, for a 2-phase signal plan operating at a 60-second cycle length with a 4-second intergreen interval, the approach operates at a capacity of 780 veh/h (1800×26/60). Alternatively, an approach to a 4-phase traffic signal operating at the same 60-second cycle length and an identical 4-second intergreen interval operates at a capacity of 330 veh/h (1800×11/60). Consequently, the total traffic demand was altered in the 4-phase scheme in order to ensure consistency in the volume-to-capacity ratios for the two phasing schemes, as summarized in Table 5.2.

Table 5.2: V/C Ratios for Total Demands

Total Demand Scenario	Total Demand (veh/h)		Volume-to-capacity Ratio
	2-Phase	4-Phase	
1	800	672	0.51
2	1000	844	0.64
3	1200	1016	0.77
4	1400	1188	0.90
5	1600	1360	1.03

Five traffic demand levels were considered in the study in order to quantify the sensitivity of the results to the level of congestion. The five demand levels resulted in approach volume-to-capacity ratios that ranged from 0.51 to 1.03, as summarized in Table 5.2.

The literature indicates that the system-wide negative impacts of transit signal priority result when the approaches not receiving priority operate at high volume-to-capacity ratios (v/c greater than 90 percent). In order to investigate this hypothesis, the 2-phase scheme was loaded with six demand distribution scenarios, as summarized in Table 5.3. In these scenarios the v/c ratio ranged from a significant difference (0.13 versus 1.41) to equal v/c ratios. The approach at which the transit vehicle arrived was also varied in order to vary the level of congestion on the approach receiving priority.

It is also proposed that the base signal timing plan impacts the system-wide benefits of transit signal priority. Consequently, sub-optimal signal timings are introduced in order to test the proposed hypothesis. Specifically, the impact of sub-optimal cycle lengths and sub-optimal phase splits were considered in the analysis, as summarized in Table 5.1 (variables D and F).

Finally, the study investigates the impact of dwell time at a nearside bus stop that is located within the detection range of the traffic signal. The hypothesis that is proposed is that the system-wide disbenefits of transit signal priority increase as the transit vehicle dwell time increases because the signal tries to accommodate the bus while it is still stopped at the bus stop.

5.4 Simulation Results

As mentioned earlier, a number of hypotheses were identified as part of this study. The objective of the study is to establish the appropriateness of these hypotheses, which are summarized as follows:

a. In general transit priority provides benefits to transit vehicles that receive priority. These benefits are highly dependent on the time of arrival of the transit vehicle within the cycle length.
b. Transit priority has a marginal system-wide impact for low traffic demands, however as the demand increases the system-wide disbenefits of transit priority increases.
c. The system-wide impact of transit priority is dependent on the frequency of transit vehicles. It is hypothesized that higher frequency of transit vehicles results in larger system-wide disbenefits.
d. Transit priority impacts are sensitive to demand distribution at a signalized intersection. Transit vehicle arrivals on heavily congested approaches may result in system-wide benefits if the conflicting approaches are not congested. Alternatively, transit vehicle arrivals on lightly congested approaches may produce significant system-wide disbenefits if the conflicting approaches are heavily congested.
e. The system-wide benefits of transit priority are dependent on the phase at which the transit vehicles arrive especially if the cycle length is maintained within the priority logic. It is hypothesized that larger system-wide disbenefits occur for transit vehicle arrivals during later phases.
f. Transit vehicle dwell times at near-side bus stops can have significant system-wide impacts on the potential benefits of transit signal priority. It is hypothesized that the system-wide disbenefits increase with an increase in bus stop dwell times if the bus stop is located within the detection range of the traffic signal.

5.4.1 Impact of Traffic Demand

In order to quantify the impact of traffic demand on the potential benefits of transit priority, a total of 80 simulation runs were executed. These 80 runs included 8 bus departure times, 2 phase schemes, and 5 levels of total traffic demand (variables ABC in Table 5.1). Figure 5.5 and Figure 5.6 illustrate how the average impacts of transit priority on transit vehicles vary as a function of the level of congestion at the signalized intersection for a transit demand of 12 veh/h. The figures illustrate that as the traffic demand increases, the average delay, average vehicle stops, and average fuel consumption of transit vehicles also increases in both the 2-phase and the 4-phase scheme. Figure 5.5 and Figure 5.6 also illustrate that regardless of the volume-to-capacity ratio, transit priority can decrease the average delay, average stops, and average fuel consumption of transit vehicles when compared with no transit priority. Specifically, for the two-phase scheme, the average delay of transit vehicles decreases by 28.7 and 29.8 percent as a result of transit signal priority for the 2-phase and 4-phase schemes, respectively. Interestingly, the figures indicate that the benefits to transit vehicles increases as the level of congestion increases. The reason for this finding will be described later in this section.

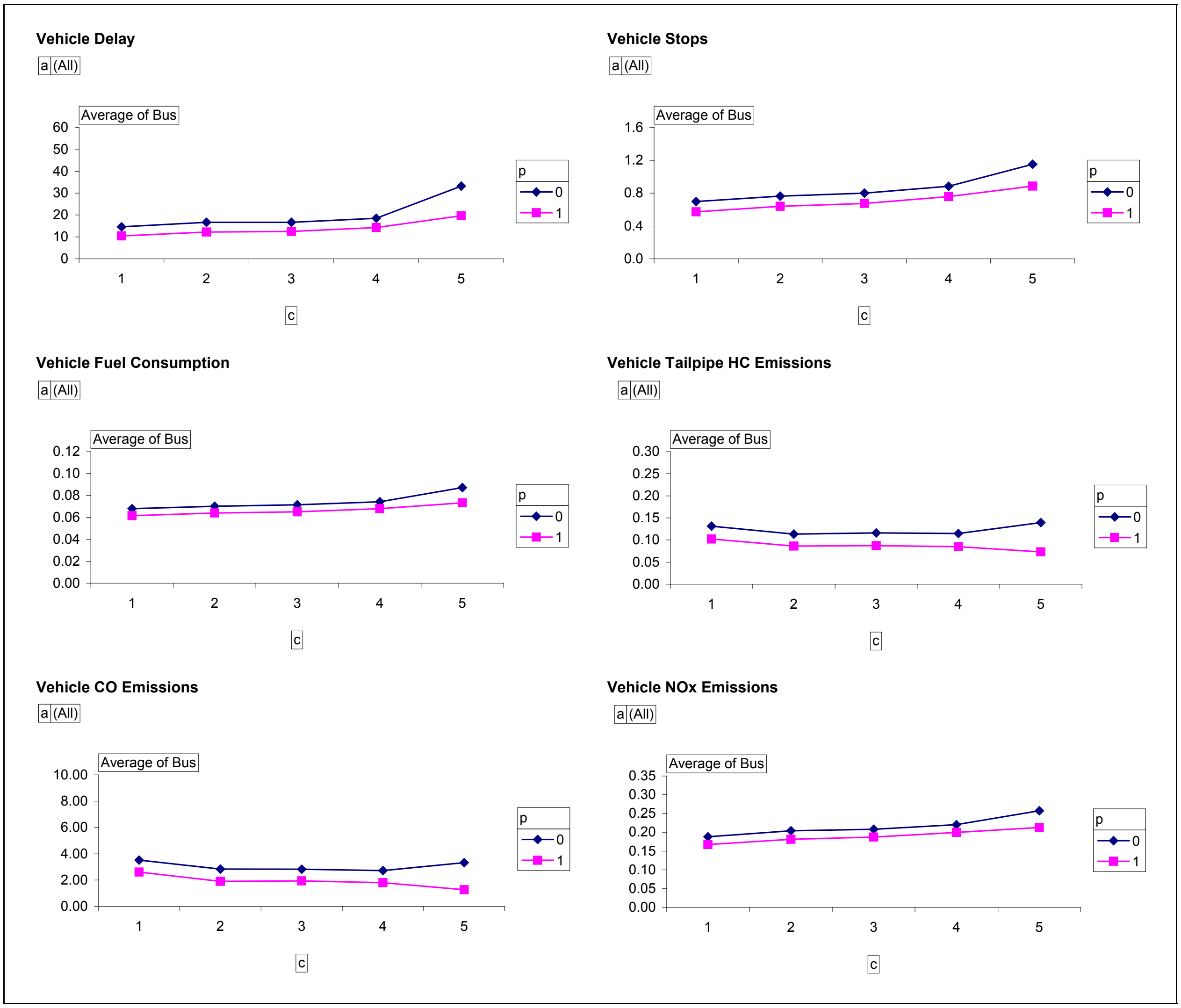


Figure 5.5: Average Transit Vehicle Impacts of Transit Priority (2-phase Signal Operation – Transit Demand of 12 veh/h)

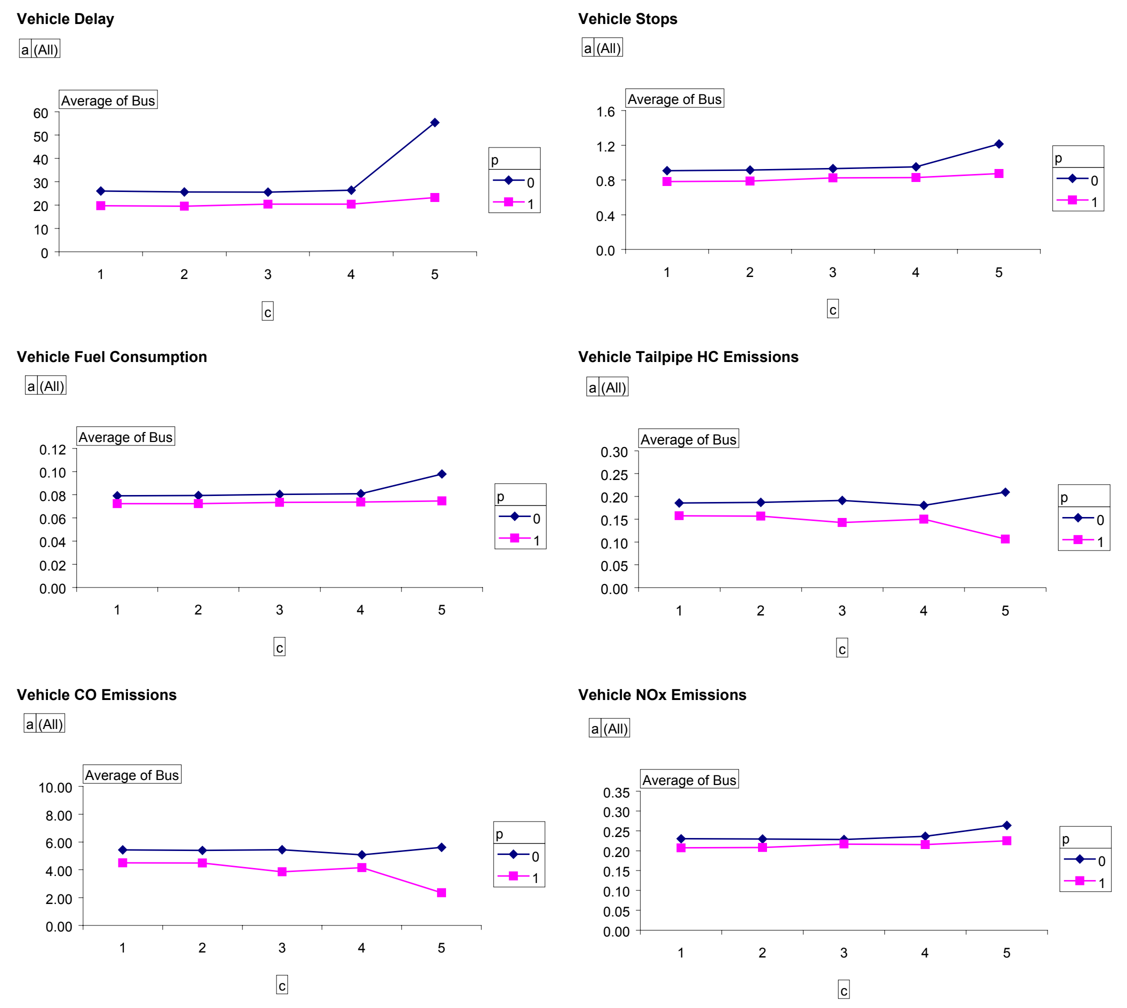


Figure 5.6: Average Transit Vehicle Impacts of Transit Priority (4-phase Signal Operation – Transit Demand of 12 veh/h)

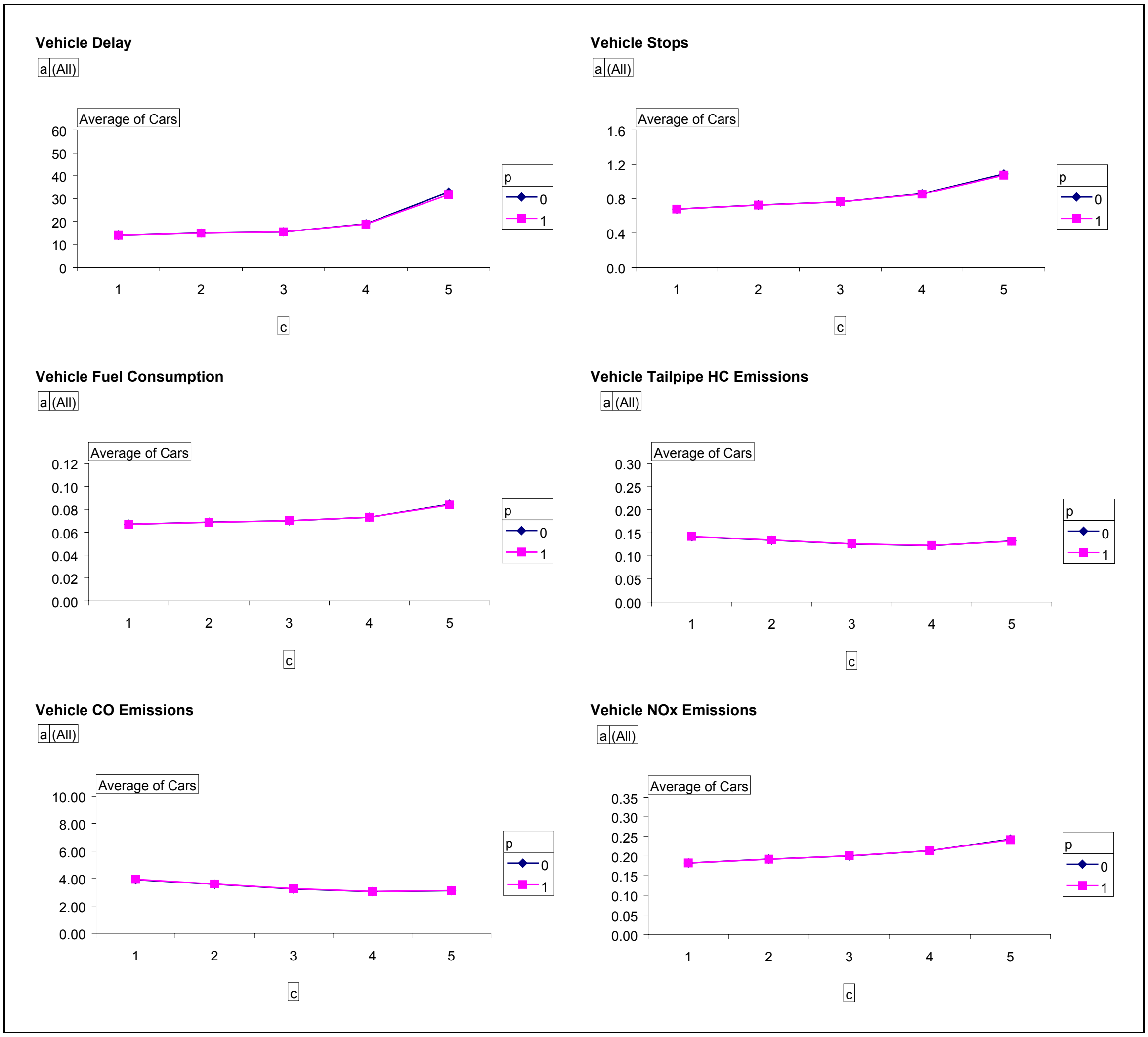


Figure 5.7: Average Impacts of Transit Priority on cars (2-phase Signal Operation – Transit Demand of 12 veh/h)

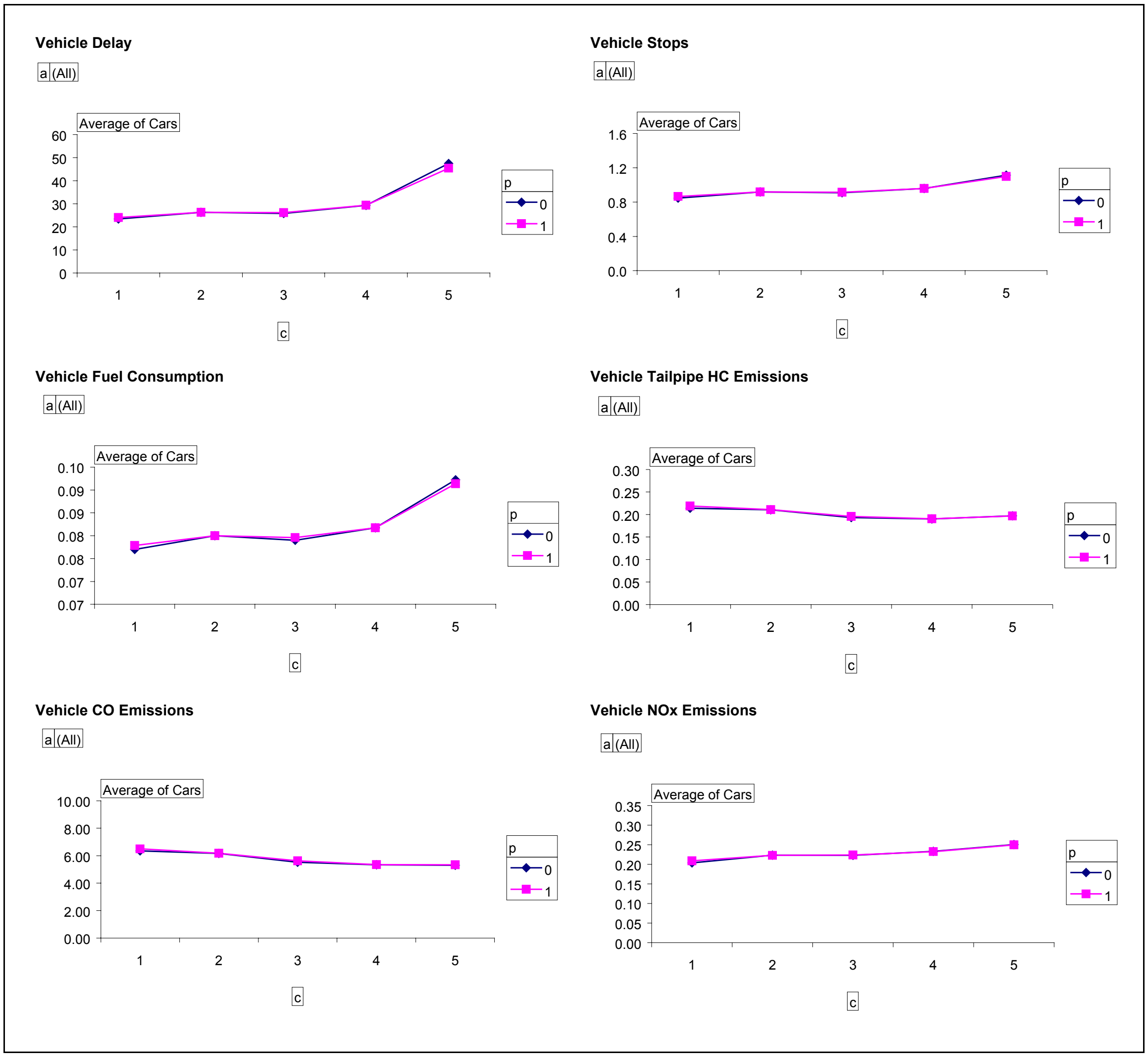


Figure 5.8: Average Impacts of Transit Priority on cars (4-phase Signal Operation – Transit Demand of 12 veh/h)

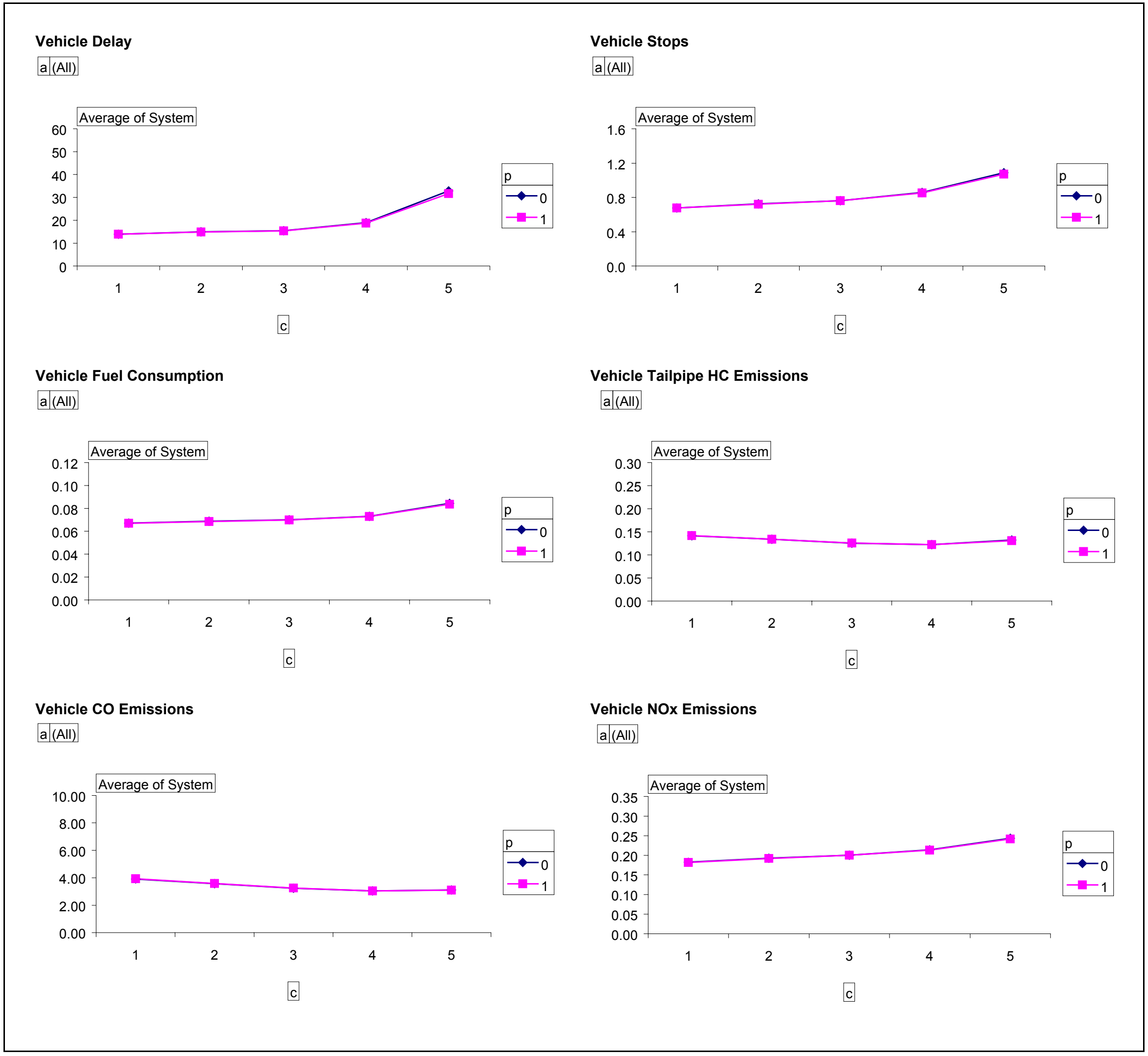


Figure 5.9: Average System-wide Impacts of Transit Priority (2-phase Signal Operation – Transit Demand of 12 veh/h)

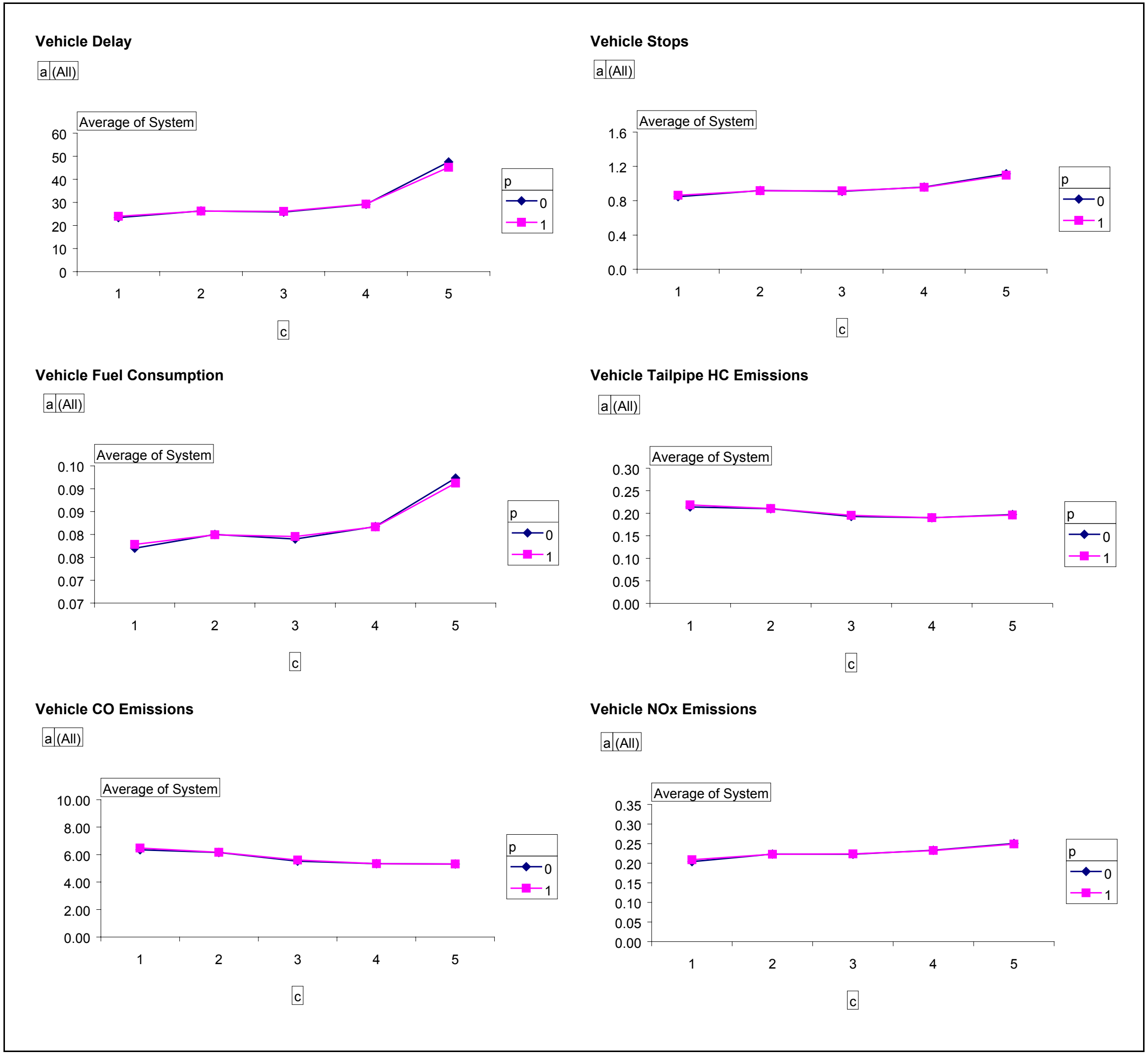


Figure 5.10: Average System-wide Impacts of Transit Priority (4-phase Signal Operation – Transit Demand of 12 veh/h)

Figure 5.7 and Figure 5.8 illustrate the average impacts of transit priority on passenger vehicles. The figures show that as the traffic demand increases, the average delay, average vehicle stops, and average fuel consumption of the non-transit vehicles increases for both the 2-phase scheme and the 4-phase scheme. The results indicate that providing transit priority to transit vehicles has a marginal effect on the average vehicle delay (a 0.09 percent decrease in the case of the 2-phase scheme and 0.01 percent decrease in the 4-phase scheme), average vehicle stops, and average fuel consumption of private vehicles. It should also be noted that the CO emissions decreased as the level of congestion increased, which appears to be counter intuitive. A close analysis of the results indicates that vehicle accelerations within the simulation environment are less aggressive when vehicles interact with other vehicles, which results in an overall reduction in average vehicle CO emissions. Validation of this observation using field data is required to ascertain that vehicle accelerations are less aggressive as congestion increases.Figure 5.9 and Figure 5.10 illustrate the average system-wide impacts of transit priority (impacts on transit and non-transit vehicles). The Figures show that when the traffic demand grows, the average delay, average vehicle stops, and average fuel consumption of the entire system will increases in both the 2-phase scheme and the 4-phase scheme, and that providing transit priority to transit vehicles has a marginal system-wide effect on the average delay, average vehicle stops, and average fuel consumption. Specifically, for the 2-phase scheme the average delay decreases by 1.3 and 0.3 percent for the 2-phase and 4-phase schemes, respectively.

Figure 5.11 illustrates how the maximum benefits to a single transit vehicle traveling in the eastbound direction vary for the 2-phase scheme. The bus departs 15 seconds into the cycle and requires 15 seconds to travel the length of the link (traveling at 60 km/h over a distance of 0.25km). In the case of no priority, the transit vehicle would have to come to a complete stop at the intersection since it arrives during the amber interval at the conclusion of the first phase green interval. Alternatively, when transit priority is allocated to the bus, the first phase is extended to allow the bus to proceed through the intersection without having to stop. The difference in the priority and no-priority curves is constant and equals to the duration of the second phase given that the vehicle arrives just as the second phase starts.

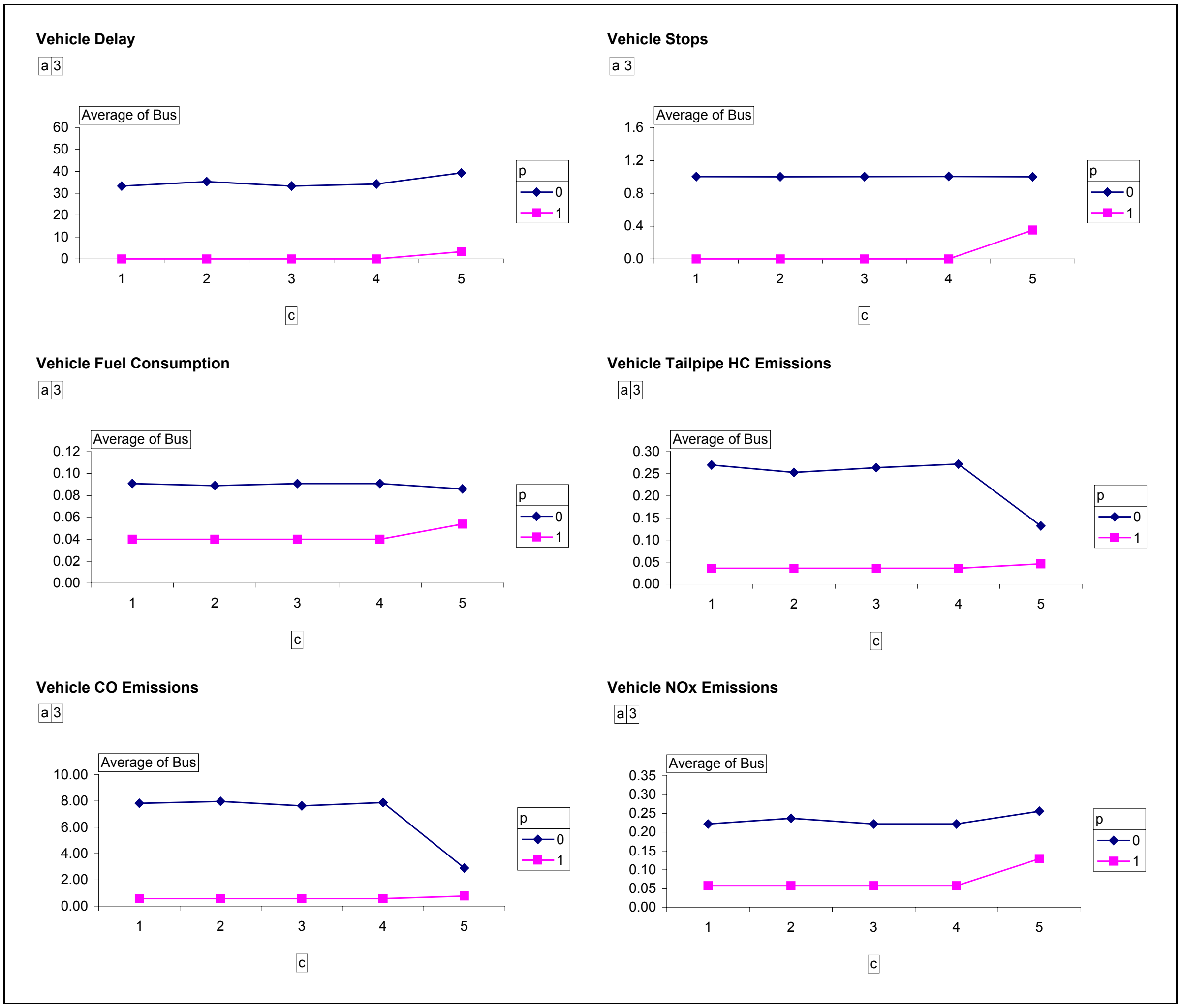


Figure 5.11: Transit Vehicle Impacts of Transit Priority (Vehicle Departure at 15 seconds)

Figure 5.12 illustrates the variation in the various measures of effectiveness for the transit vehicle that departs 7.5 seconds into the cycle. In this case the bus arrives at the signalized intersection 22.5 seconds into the cycle and thus can proceed through the intersection without having to stop. However, as the demand increases longer queues are formed upstream the intersection causing the transit vehicle to be delayed and thus missing the first phase green interval, which concludes 26 seconds into the cycle. Alternatively, in the case of transit signal priority although the bus is delayed by the queue formation upstream of the traffic signal, the green interval is extended to allow the transit vehicle to proceed without having to wait for the duration of the entire second phase. This finding explains why larger benefits were experienced by the transit vehicles for the higher demands in Figure 5.5 and Figure 5.6.

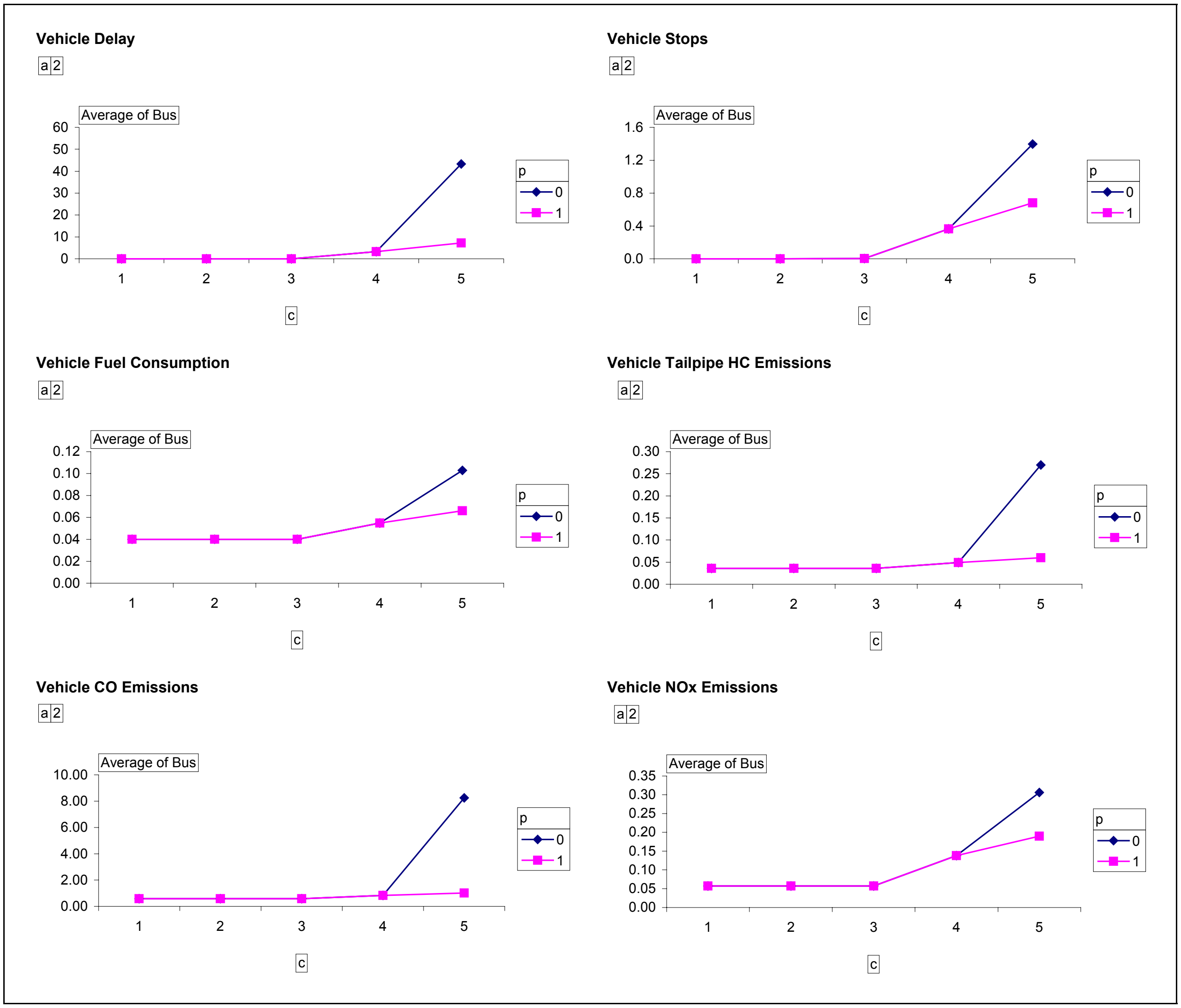


Figure 5.12: Transit Vehicle Impacts of Transit Priority (Vehicle Departure at 7.5 seconds)

In summary, the analysis demonstrates that in general transit priority provides benefits to transit vehicles that receive priority and these benefits are highly dependent on the time of arrival of the transit vehicle within the cycle length. In this case minor negative impacts were incurred on the general automobile traffic.

5.4.2 Impact of Transit Demand

The previous analysis indicated that while transit priority provided benefits to the transit vehicles, no disbenefits were incurred on the general traffic. In order to ascertain that these findings were not caused by the fact that the transit vehicle demand was low, the next step of the analysis was to investigate the system-wide impacts of transit priority for a larger transit vehicle demand. Specifically, a transit vehicle headway of 2 minutes (demand of 36 veh/h) and 1 minute (demand of 60 veh/h) were considered.

As illustrated in Figure 5.13, Figure 5.14, and Figure 5.15 the higher transit vehicle demand of 36 veh/h while providing benefits to the transit vehicles did not result in negative system-wide impacts for levels of congestion ranging from a v/c ratio of 0.50 to 1.03. Similarly, Figure 5.16, Figure 5.17, and Figure 5.18 illustrate a similar trend of behavior with reductions in delays for transit vehicles and insignificant system-wide changes in traffic demand.

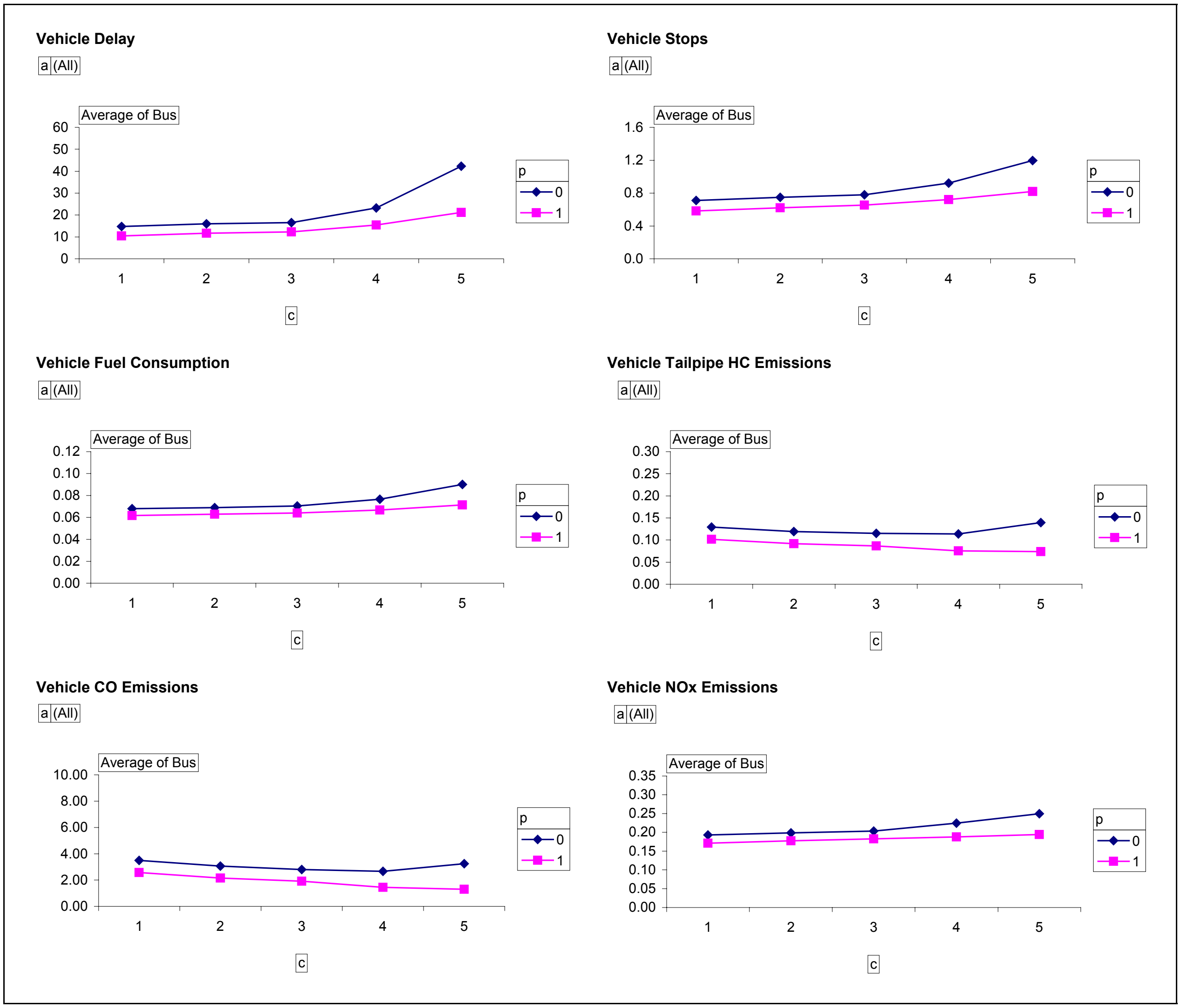


Figure 5.13: Average Transit Vehicle Impacts of Transit Priority (2-phase Signal Operation – Transit Demand of 36 veh/h)

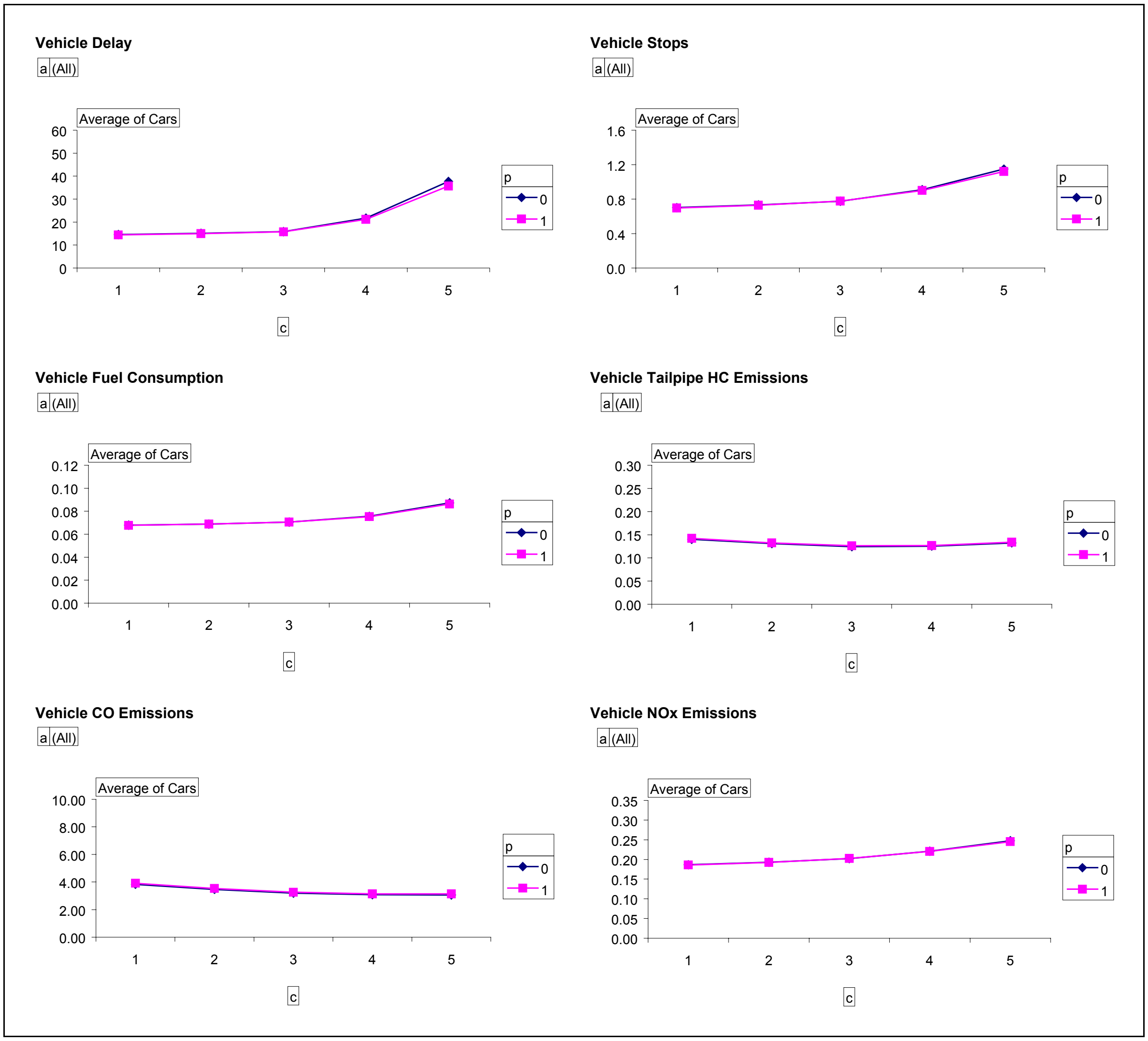


Figure 5.14: Average Private Vehicle Impacts of Transit Priority (2-phase Signal Operation – Transit Demand of 36 veh/h)

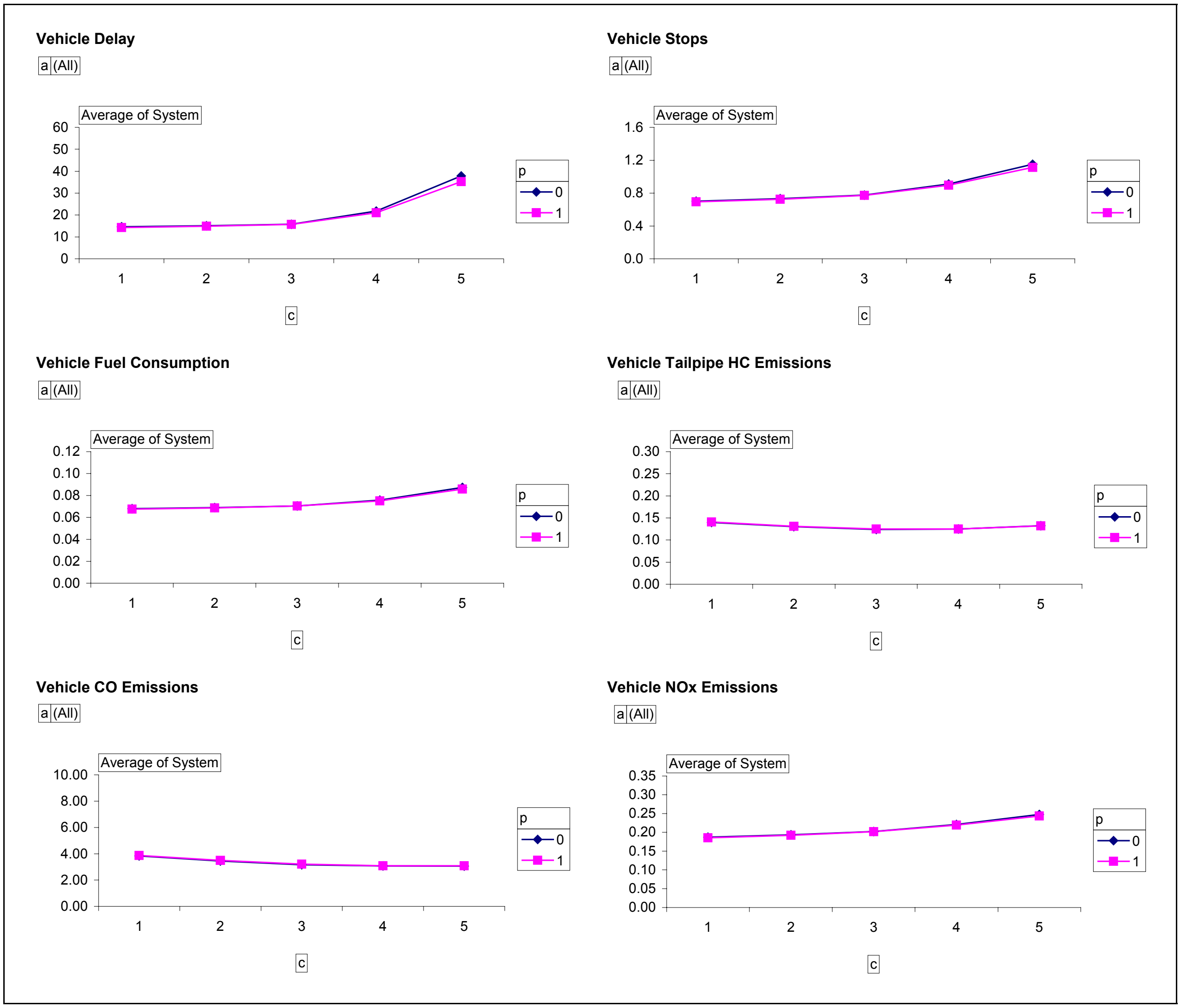
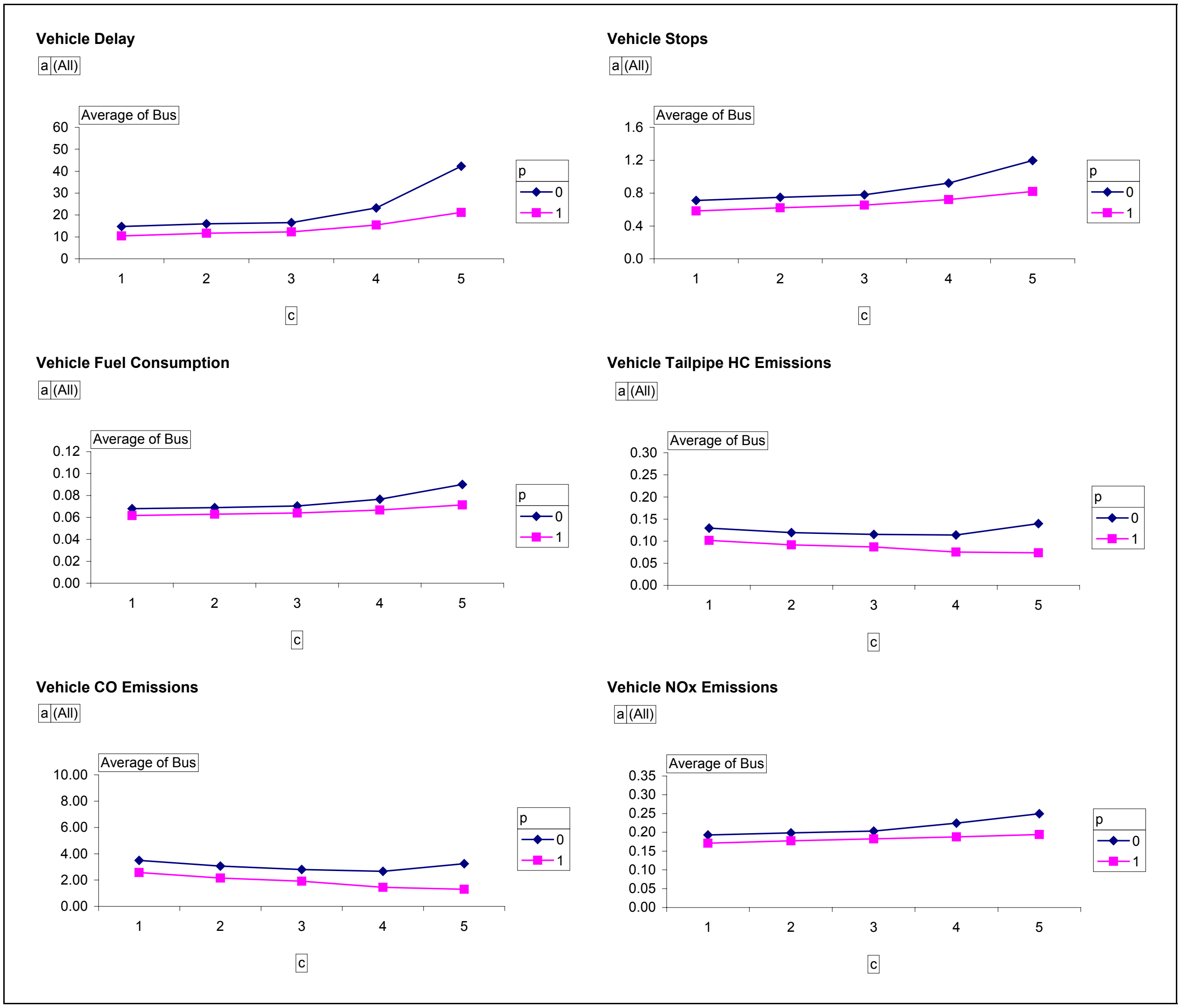


Figure 5.15: System-wide Impacts of Transit Priority (2-phase Signal Operation – Transit Demand of 36 veh/h)



Vehicle Delay

Vehicle Stops

Vehicle Fuel Consumption

Vehicle Tailpipe HC Emissions

Vehicle CO Emissions

Vehicle NOx Emissions

Figure 5.16: Average Transit Vehicle Impacts of Transit Priority (2-phase Signal Operation – Transit Demand of 60 veh/h)

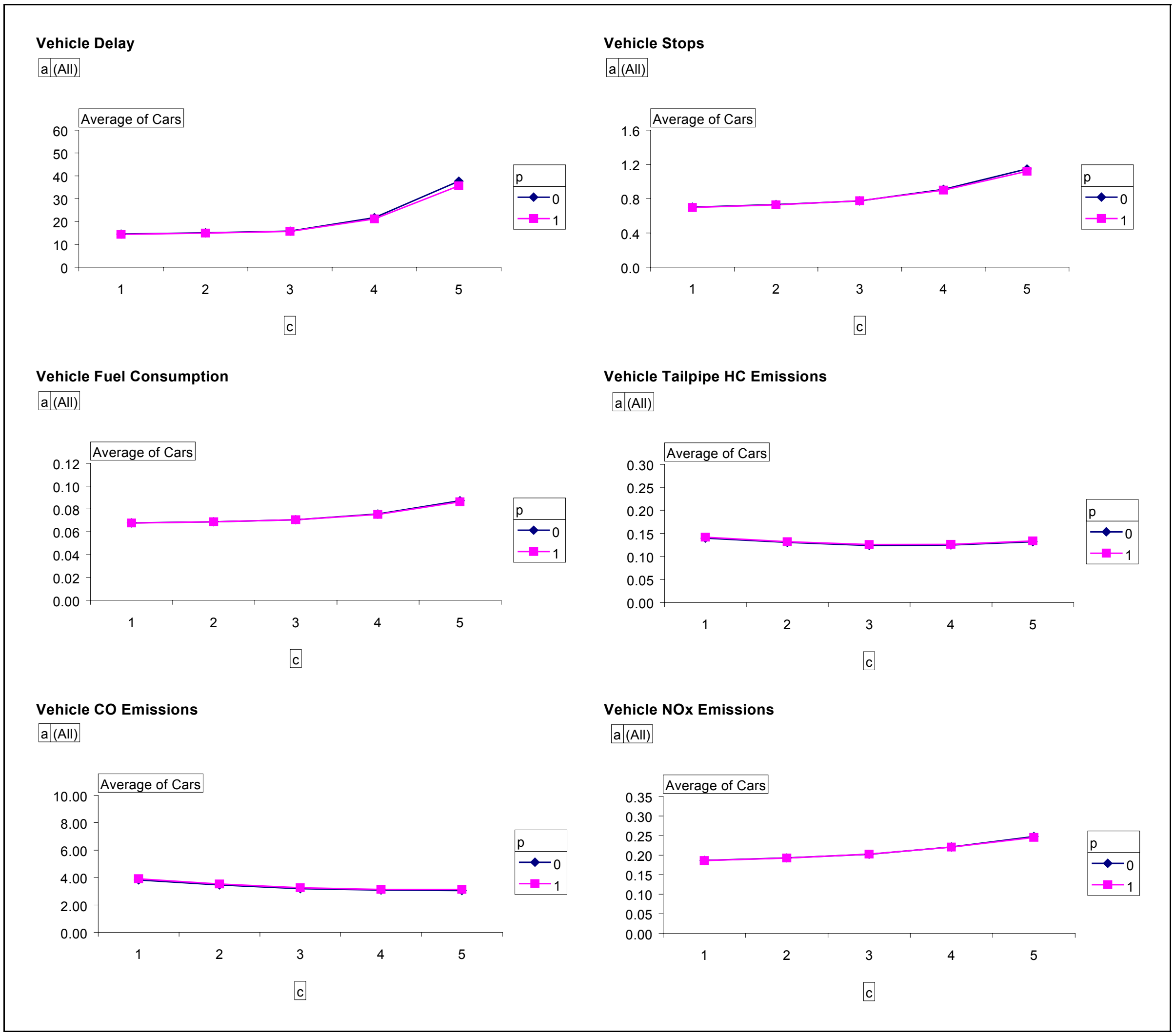


Figure 5.17: Average Private Vehicle Impacts of Transit Priority (2-phase Signal Operation – Transit Demand of 60 veh/h)

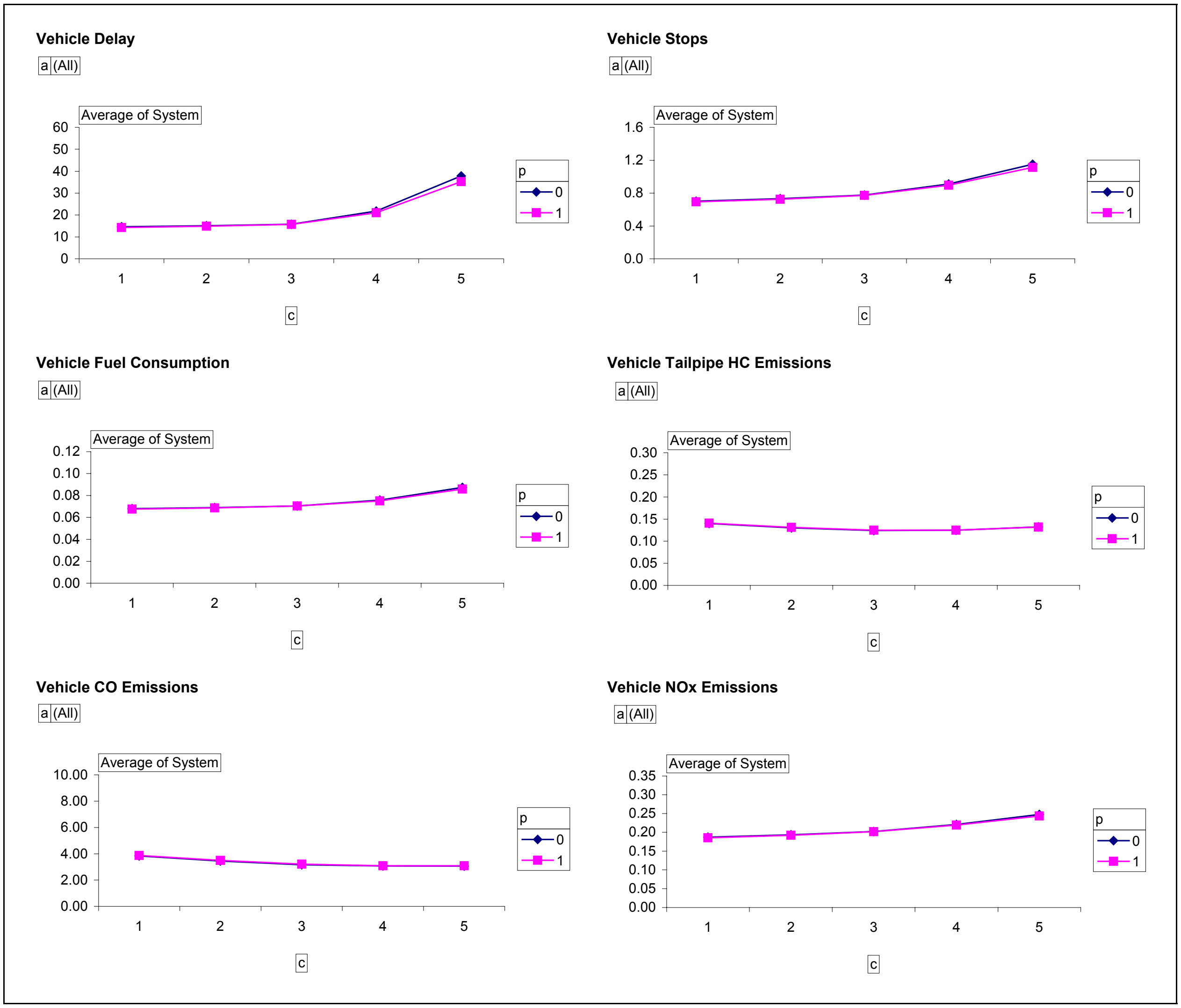


Figure 5.18: Average System-wide Impacts of Transit Priority (2-phase Signal Operation – Transit Demand of 60 veh/h)

In Figure 5.13, transit vehicles experience a reduction of 33.0 percent in average vehicle delay when transit priority is granted to the transit vehicles. In the case of the 4-phase scheme the reduction in average delay for transit vehicles as a result of transit priority is approximately 37.9 percent. An increase in the transit vehicle demand to 60 veh/h for a 2-phase signal timing scheme, reduces the average delay experienced by transit vehicles by 32.9 percent compared to the base no priority case, as illustrated in Figure 5.16. Larger reductions in transit vehicle delay were observed for the 4-phase scheme (reductions of 44.7 percent). The higher benefits of transit priority for the 4-phase scheme are attributed to the fact that the percentage of green time allocated to a specific approach is less for the 4-phase scheme compared to the 2-phase scheme. Consequently, the transit vehicles are more likely to arrive when the traffic signal indication is red in the case of no priority, thus providing more opportunities to reduce transit vehicle delays by extending the green interval.

The study also indicates that the benefits of transit signal priority to the vehicles receiving priority increases as the level of congestion increases for two reasons. The first reason is attributed to the fact that the base case involves higher delay to transit vehicles as the approach demand increases. The second reason is that because the transit vehicle may be queued upstream the intersection within the detection range, there is a longer temporal opportunity for the vehicle to be detected.

Figure 5.14 and Figure 5.17 demonstrate the increase in traffic demand has a marginal impact on the general traffic and a marginal impact on the system as a whole. For example, an increase in the transit demand to 36 veh/h still results in minor benefits to the general traffic in the range of 2.0 and 1.2 percent for the 2-phase and 4-phase schemes, respectively. In addition, system-wide delay reductions in the range of 3.0 and 2.5 percent are observed for the 2-phase and 4-phase schemes, respectively.

An additional increase in transit demand to 60 veh/h results in similar findings. Specifically, compared to the base “no priority” scenario reductions in delay in the range of 2.0 and 1.4 percent are observed for the 2-phase and 4-phase schemes, respectively. In addition, system-wide reductions in vehicle delay in the range of 3.0 and 4.3 percent are observed for the 2-phase and 4-phase schemes, respectively.

5.4.3 Impact of Demand Distribution and Phase Requesting Priority

Given that the transit signal priority logic that was tested provided vehicle priority within traffic signal coordination (i.e. maintained a constant cycle length), it was important to investigate the sensitivity of the results to the phase requesting priority. Specifically, two batches of simulation runs were conducted in which transit vehicles traveled along the eastbound direction (arrivals during phase 1) and a series of runs in which transit vehicles traveled in the northbound direction (arrivals during phase 2). In addition, 11 demand distribution levels and two signal timing schemes were considered. In the first scheme, the signal timings were held fixed at a 50:50 phase split while in the second scheme the signal timings were optimized to reflect the different demand distributions. Specifically, the phase lengths were set proportional to the critical volume-to-capacity ratios for each phase. It should be noted, that the volume-to-capacity ratio varied considerably for the 50:50 phase split scheme, as demonstrated in Table 5.3.

Table 5.3: V/C Ratios at Signalized Approaches for 2-Phase 50:50 Phase Split

Demand Distribution Scenario	Eastbound		Northbound	
	Demand	v/c Ratio	Demand	v/c Ratio
1	100	0.13	1100	1.41
2	200	0.26	1000	1.28
3	300	0.38	900	1.15
4	400	0.51	800	1.03
5	500	0.64	700	0.90
6	600	0.77	600	0.77

The objectives of this analysis are two-fold. First, the analysis attempts to investigate the sensitivity of results to the phase requesting priority. Second, the analysis attempts to investigate the impact of different demand distributions at the approaches to a signalized intersection on the benefits of transit priority.

Figure 5.19 illustrates the variation in system-wide impacts of transit priority for a two-phase 50:50 phase split operation and a transit vehicle demand of 12 veh/h. It should be noted from the figure that the average system delay decreases as the demands on the competing approaches tend to be evenly distributed (case 6 on the x-axis). The higher delays for the non-equal demands result from the non-optimal phase split setting (50:50 phase split). The figure illustrates the impacts of transit vehicle priority for vehicle arrivals during phase 1 (eastbound arrivals) and phase 2 (northbound arrivals). Counter to intuition, the figure clearly illustrates a minor system-wide impact of transit signal priority when priority is allocated to phase 1. This finding can be explained by the fact that in most cases the signal timings are not altered by the signal priority logic because arrivals during the green interval of phase 1 and after the conclusion of the green interval of phase 1 do not result in any changes to the signal timings. The only case in which the signal timing can be altered is when the transit vehicle arrives just before the conclusion of the green interval of phase 1. A similar behavior is observed for a higher transit vehicle demand, as illustrated in Figure 5.20, except that the transit priority does incur a minor system-wide increase in delay because of the higher transit demand.

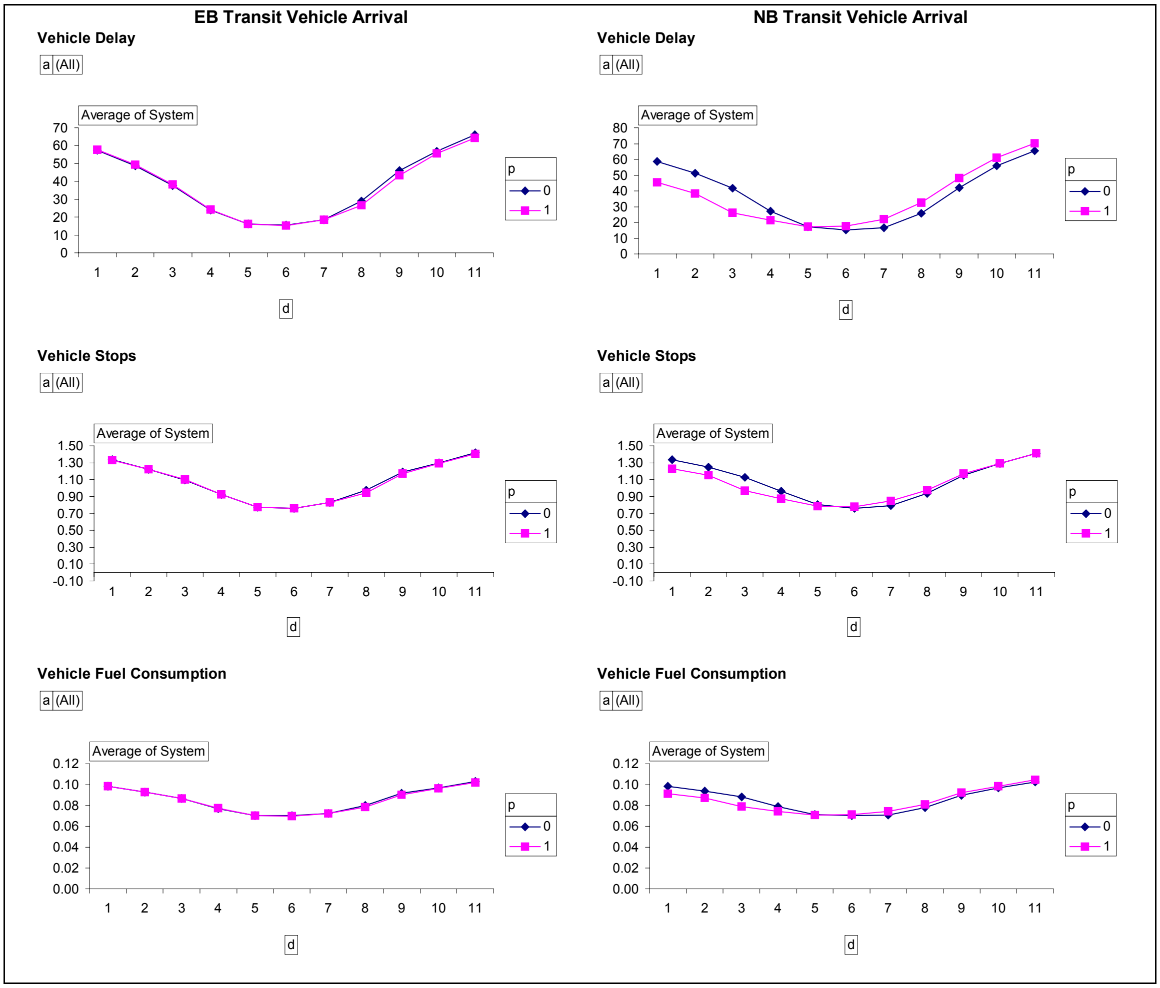


Figure 5.19: Variation of Transit Priority System-wide Benefits as a Function of Demand Distribution (2-Phase Signal Operation with 50:50 Split – Transit Demand of 12 veh/h)

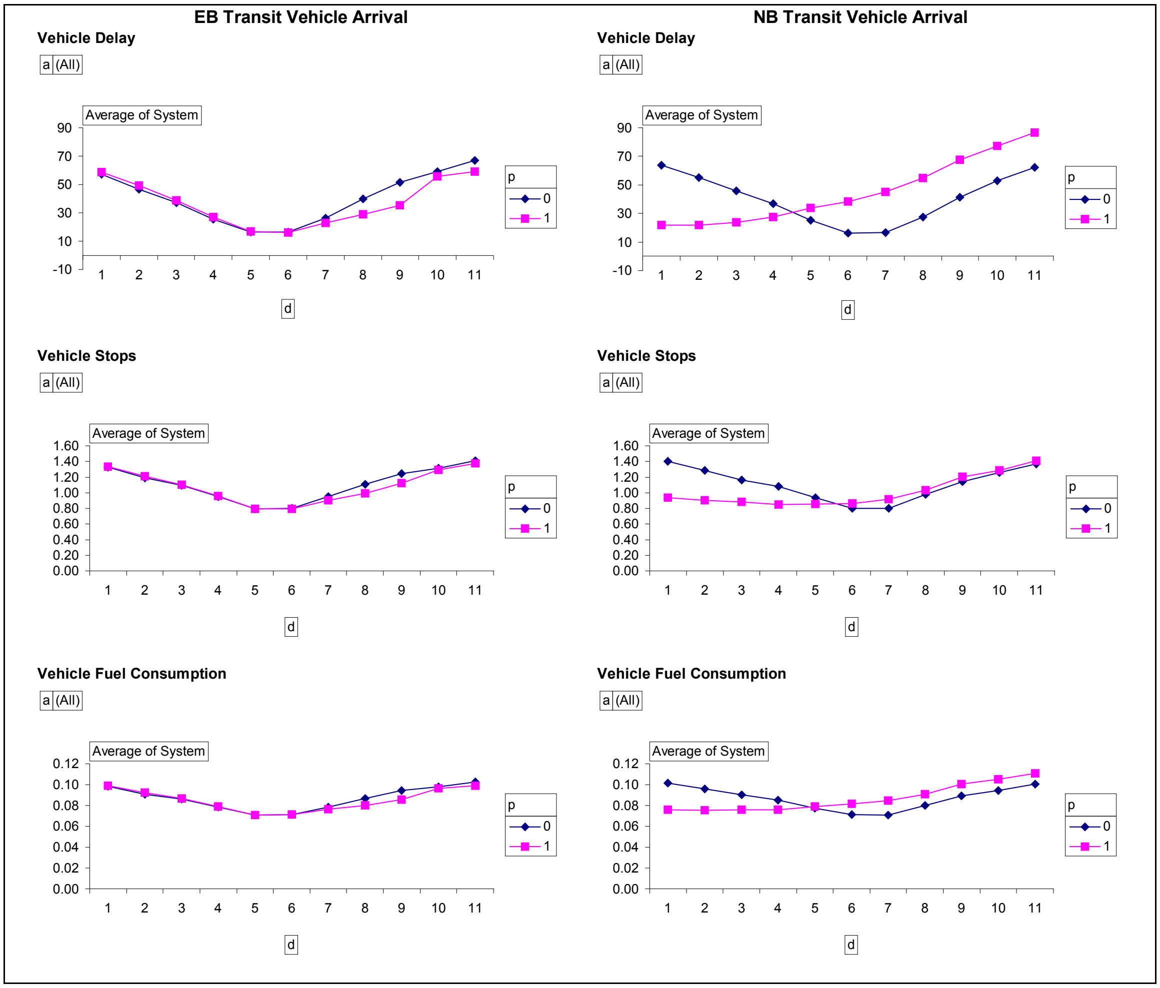


Figure 5.20: Variation of Transit Priority System-wide Benefits as a Function of Demand Distribution (2-Phase Signal Operation with 50:50 Split – Transit Demand of 60 veh/h)

Alternatively, a transit vehicle arrival in the northbound direction results in significant system-wide impacts for two reasons. First, there are more opportunities to alter the signal timings given that any transit vehicle arrival in the northbound direction while phase 1 is being served will result in an early termination of phase 1 in order to serve the priority request for phase 2. Second, the alteration of the signal timings that result from providing priority to the transit vehicle provides a better signal timing plan given that the 50:50 phase split is non-optimal for the approach volumes. Consequently, the extension of phase 2 as a result of the signal priority produces a more optimum signal-timing plan and thus system-wide benefits from transit signal priority. Figure 5.19 clearly demonstrates that the system-wide benefits of signal priority decrease as the levels of congestion on the eastbound and northbound approaches tend to be equal because the background timing plan that is in place is optimum for the arrival demands. The negative impacts of transit signal priority are further demonstrated in Figure 5.20 when there is a higher demand for signal priority.

Figure 5.21 illustrates vehicle trajectories for a transit vehicle that travels in the eastbound direction entering 15 seconds into the cycle and a transit vehicle that travels in the northbound direction entering 45 seconds into the cycle. In the first case the transit vehicle arrives during the amber of the first phase (arrives 30 seconds into the cycle) while in the second case the vehicle arrives during the amber of the second phase (60 seconds into the cycle). As illustrated in the figure, the transit priority logic differs depending on which phase receives a request for transit vehicle priority. Specifically, in the case of a transit vehicle arrival during the first phase of operation the phase is extended at 5-second increments until the transit vehicle is served. Consequently, the transit vehicle does not have to stop at the signalized intersection. Alternatively, in the case of a transit vehicle arrival during the second phase, given that the logic maintains a constant cycle length, the transit vehicle has to come to a complete stop. However, in the following cycle the green interval of the first phase is reduced to the minimum and thus the transit vehicle incurs less delay compared to the scenario in which priority is not provided.

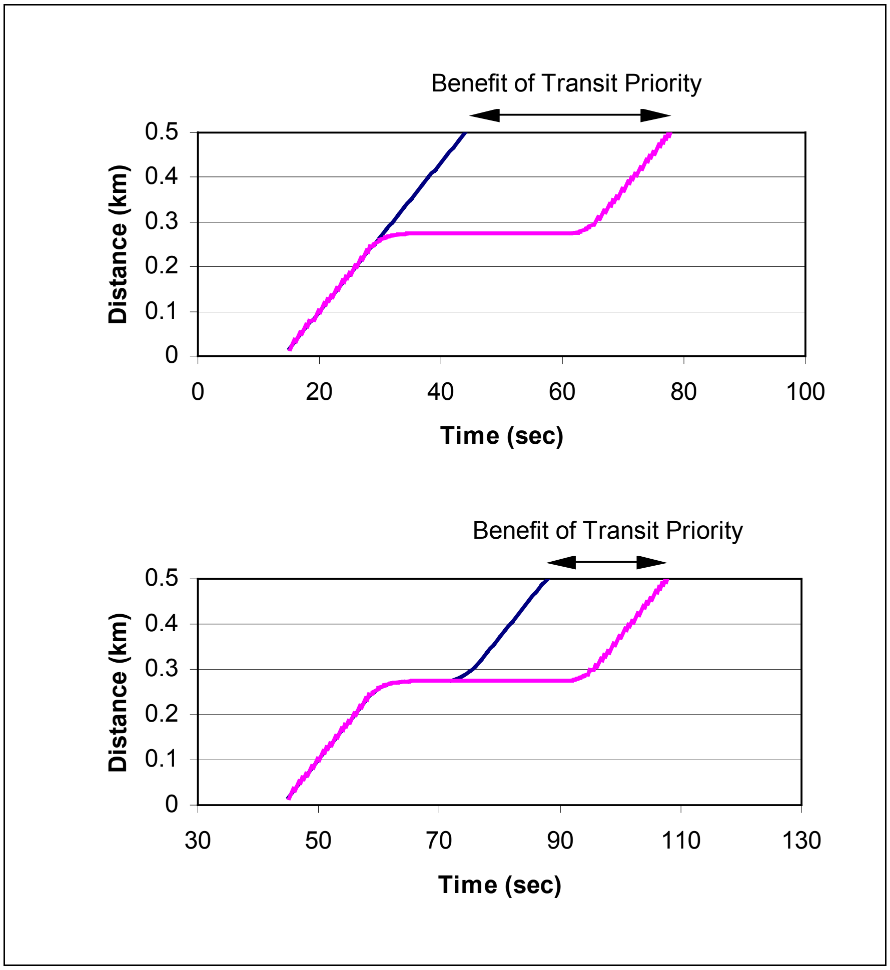


Figure 5.21: Bus Profiles of the first bus (2-Phase Signal Operation with 50:50 Split – Transit Demand of 60 veh/h)

Figure 5.22 illustrates how the system-wide impacts of transit priority vary depending on which phase requests priority in an optimized two-phase signal operation with varying conflicting demand levels and a transit vehicle headway of 5 minutes (transit vehicle demand of 12 veh/h). The figure clearly demonstrates the system-wide disbenefits of transit signal priority are minor given that the transit demand is fairly low. Again, transit priority requests during latter signal timing phases result in higher system-wide disbenefits to the system because more changes are made to the signal timings. Similarly, an increase in the transit vehicle frequency from a transit vehicle headway of 5 to 1 minute results in minor system-wide disbenefits associated with transit priority if the request for priority is during the first phase of operation. However, large system-wide disbenefits are incurred if the request for priority is made during latter phases.

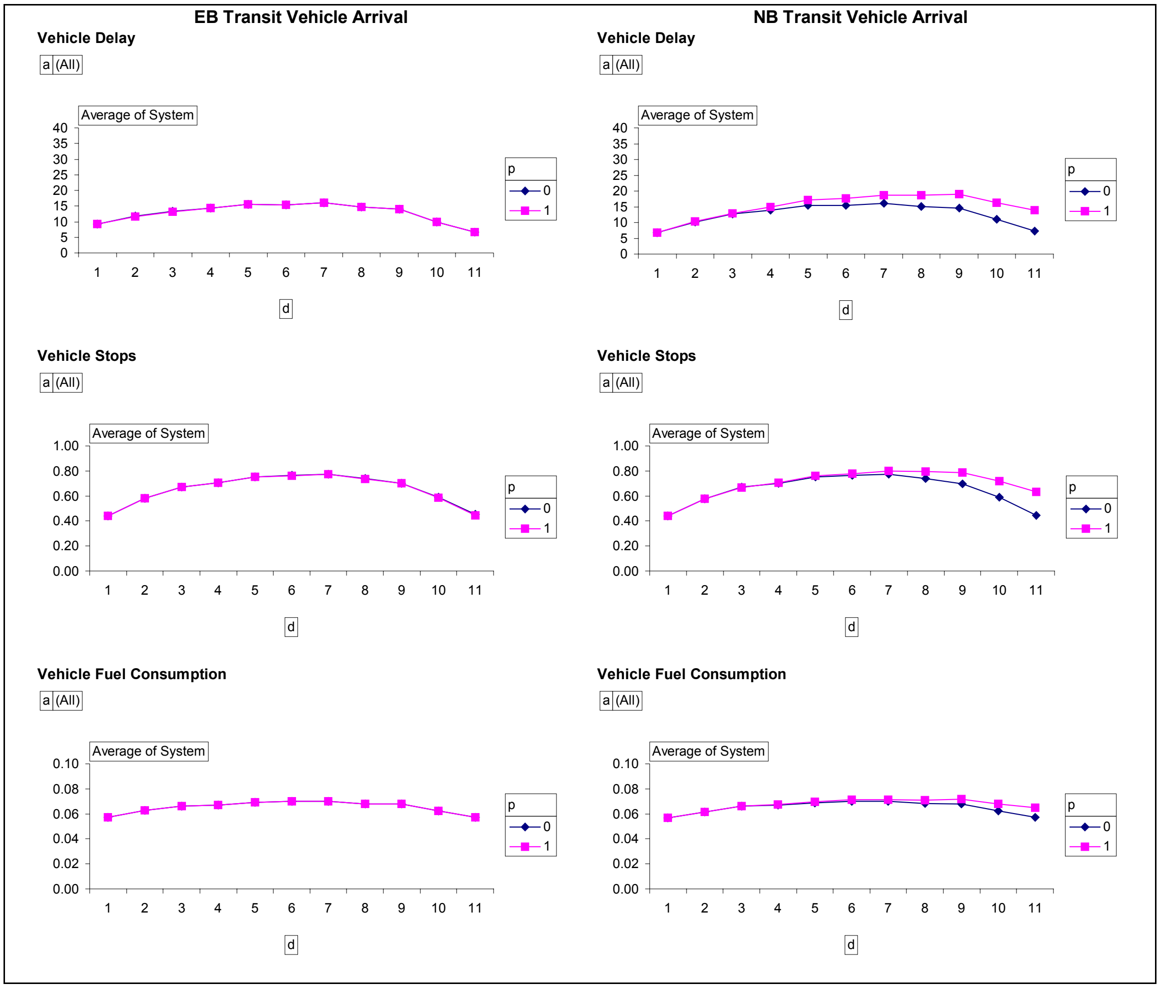


Figure 5.22: Variation of Transit Priority System-wide Benefits as a Function of Demand Distribution (2-Phase Signal Operation with Optimised Phase Split – Transit Demand of 12 veh/h)

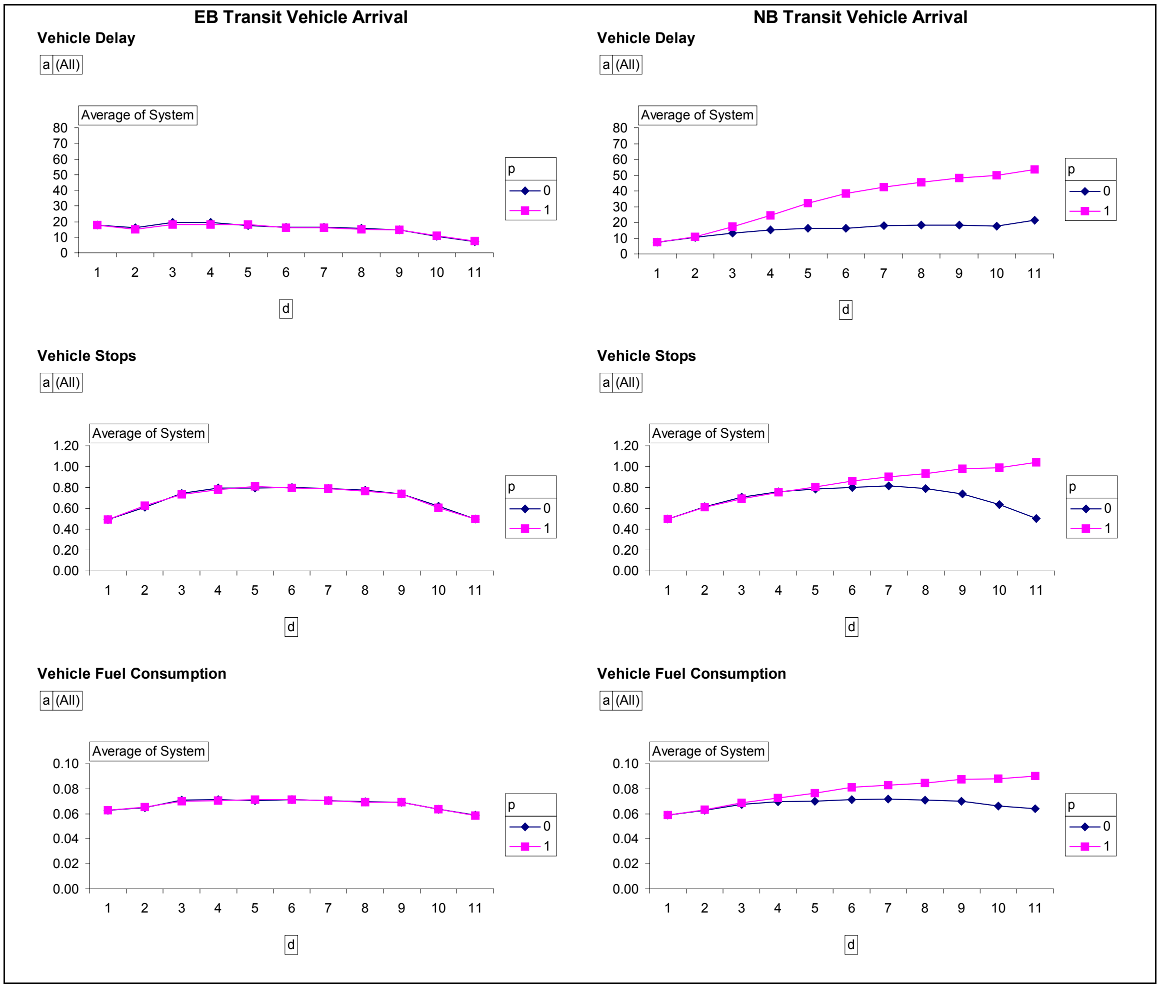


Figure 5.23: Variation of Transit Priority System-wide Benefits as a Function of Demand Distribution (2-Phase Signal Operation with Optimised Phase Split – Transit Demand of 60 veh/h)

In summary, minor changes to the signal timings to provide priority for transit vehicles has minor system-wide impacts. In addition, the study has demonstrated that the system-wide impacts of transit signal priority are highly dependent on the optimality of the base case signal timings. If providing transit signal priority improves the signal timings then system-wide benefits of transit priority are achievable.

5.4.4 Impact of Phasing Scheme

The study also considered the impact of the number of phases within a signal-timing plan on the potential impacts of transit signal priority. Specifically, a two-phase scheme and a four-phase scheme were considered. Both phasing schemes operated at the same cycle length with varying demand levels in order to maintain an identical volume-to-capacity level along the conflicting approaches. Because the 4-phase scheme incurs longer lost times, it requires a longer cycle length than does the 2-phase scheme, however for purposes of this analysis the cycle length was kept constant. Since there is a higher probability that a transit vehicle arrives at a signalized approach when the traffic signal indication is green, the two-phase scheme transit vehicles experienced lower average delays at the intersection approaches. As to the impact of the phasing scheme on transit priority, no significant effects were observed in the simulations, as demonstrated in Figure 5.5 through Figure 5.10. Specifically, an analysis of the simulation results demonstrated that in the case of the four-phase scheme, more transit vehicles were required to stop at the intersection. However, the vehicles were able to proceed through the intersection in the subsequent cycle.

5.4.5 Impact of Sub-optimal Signal Timings

The impact of sub-optimal signal timings is analyzed in two aspects in this study. First, the impact of sub-optimal cycle lengths are analyzed followed by an analysis of sub-optimal phase splits. To study the impact of cycle length and phase split, three cycle lengths and five of phase split levels were considered in the simulations, as summarized in Table 5.1. The cycle lengths that were considered in the analysis included a 40, 60, and 80-second cycle length. The five phase split levels included a 30/70, 40/60, 50/50, 60/40, and 70/30 phase split, for the east/west and north/south directions, respectively.

Figure 5.24, Figure 5.25, and Figure 5.26 illustrate the variation in transit priority impacts as a function of the traffic signal cycle length for the transit vehicles, the general traffic, and the system as a whole, respectively. The figures illustrate a minimum delay occurring at a cycle length of 40 seconds because this is closest to the optimum cycle length for the arrival volumes and saturation flow rates (C = 8/(1-1200/1800) = 24 second). Figure 5.26 demonstrates transit signal priority has minimum impact on transit vehicle delays because minimum changes are required to accommodate the transit vehicles. Specifically, the short queues and short cycle length provide little opportunity for providing transit signal priority. Since the transit demand is fairly low, the impacts of transit priority on private vehicles and the entire system are insignificant, as demonstrated in Figure 5.25 and Figure 5.26.

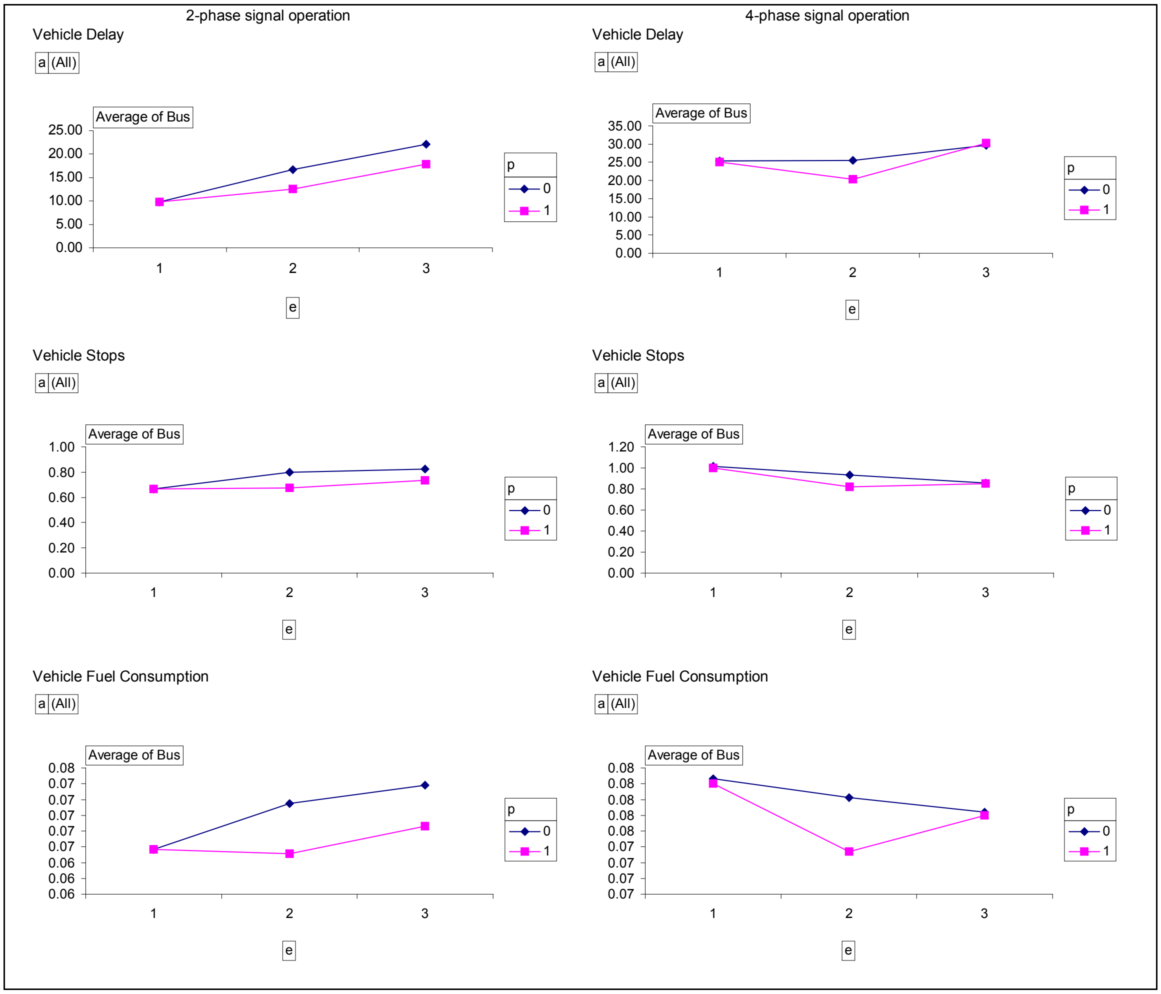


Figure 5.24: Variation Average Transit Vehicle Impacts of Transit Priority as a Function of Cycle Length (2-phase Signal Operation – Transit Demand of 12 veh/h)

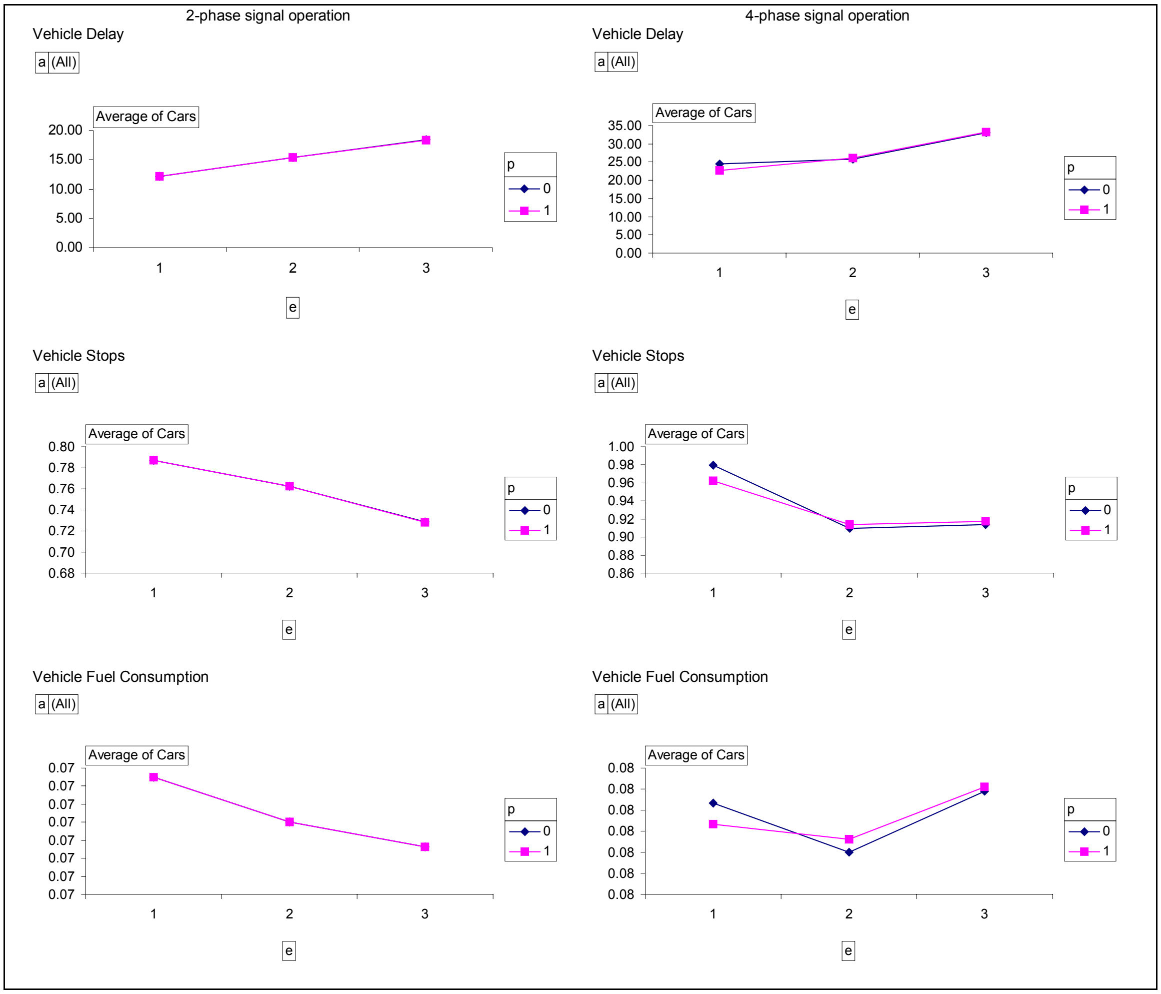


Figure 5.25: Variation Average Private Vehicle Impacts of Transit Priority as a Function of Cycle Length (2-phase Signal Operation – Transit Demand of 12 veh/h)

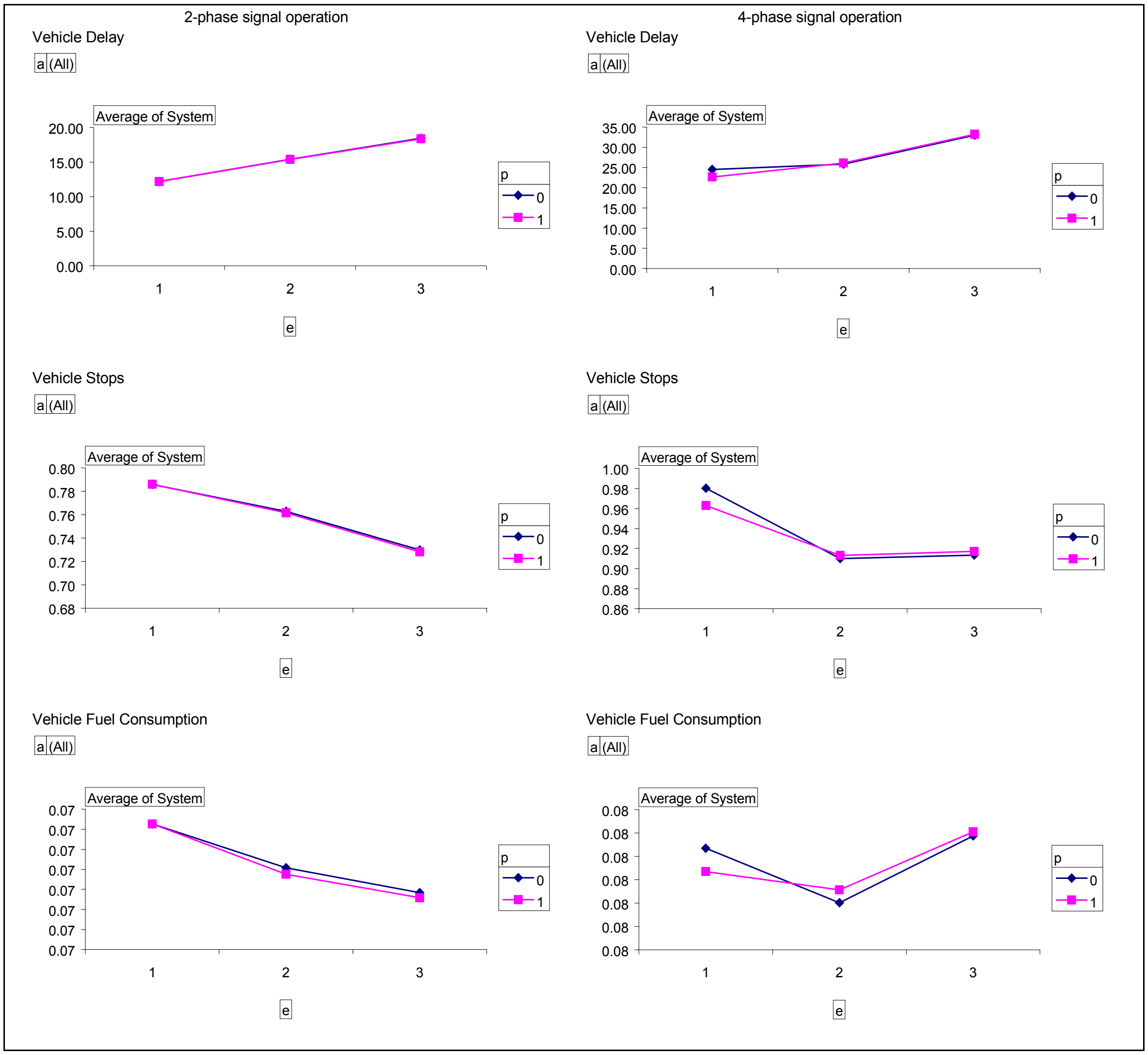


Figure 5.26: Variation Average System-wide Impacts of Transit Priority as a Function of Cycle Length (2-phase Signal Operation – Transit Demand of 12 veh/h)

Figure 5.27 and Figure 5.28 illustrate the impact of the signal-timing phase split on the benefits of transit signal priority for the transit vehicles and the system as a whole, respectively. Figure 5.27 clearly demonstrates that when phase split does not favor the approach where transit vehicles travel, transit vehicles benefit from the provision of transit priority. But when phase split already favors transit vehicles, benefits of transit priority to transit vehicles is not significant. This is because when transit vehicles are favored by phase split, they have fewer chances to be stocked in the intersection. System-wide benefits from transit priority have the same trend as the benefits to transit vehicles. System-wide benefits are achieved if the base case signal plan is sub-optimal and the transit signal priority results in an improvement in the signal timings. For example, Figure 5.28 illustrates that for the scenarios in which the green allocation to the eastbound direction was sub-optimal providing signal priority in the eastbound direction resulted in more green time being allocated to the first phase, and thus overall system-wide benefits. In the cases in which extra green time was allocated in the eastbound direction, the provision of transit priority for phase 1 has no significant system-wide impacts.

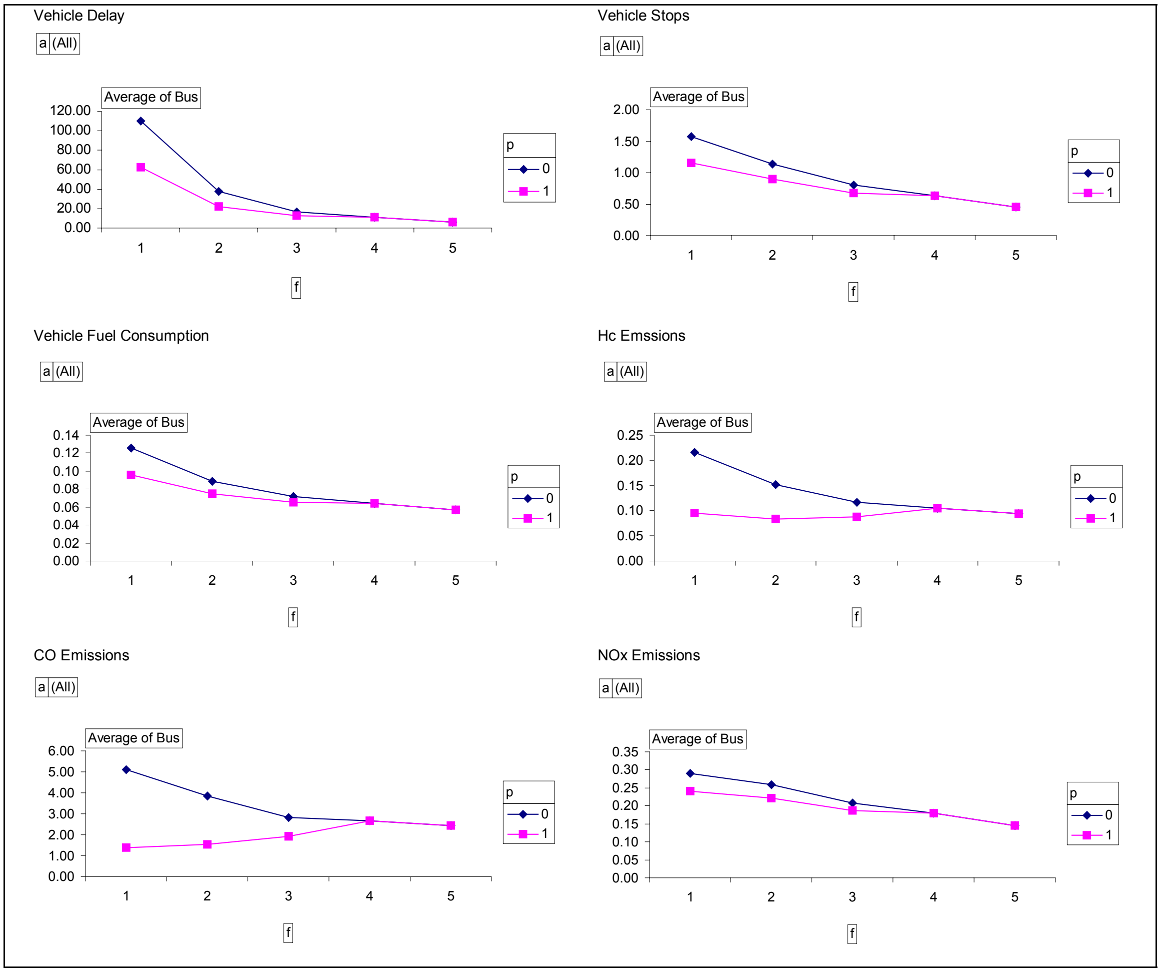


Figure 5.27: Variation Average Transit Vehicle Impacts of Transit Priority as a Function of Phase Split (2-phase Signal Operation – Transit Demand of 12 veh/h)

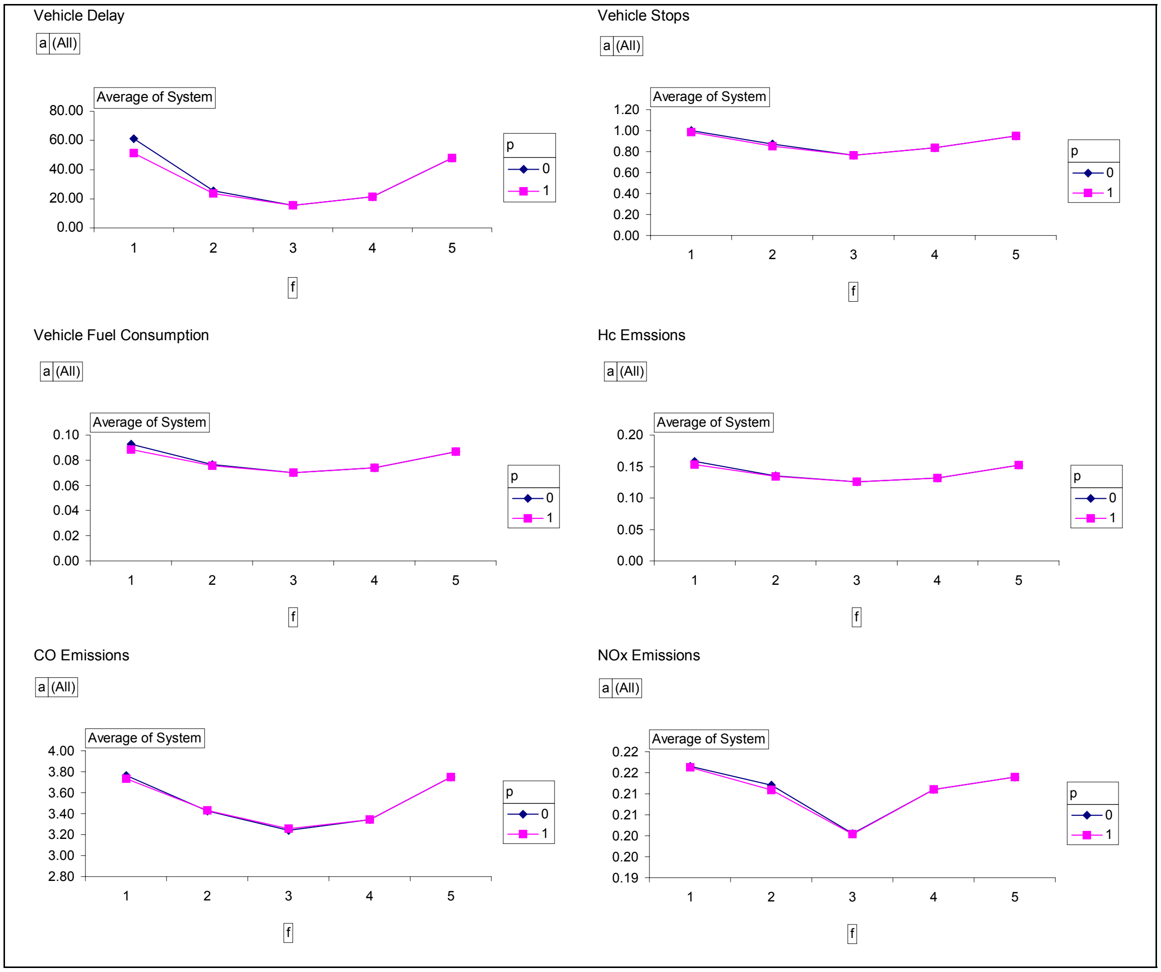


Figure 5.28: Variation Average System-wide Impacts of Transit Priority as a Function of Phase Split (2-phase Signal Operation – Transit Demand of 12 veh/h)

5.4.6 Impact of Near-side Bus Stop Dwell Times

The final sensitivity analysis that was conducted as part of this study involved analyzing the impact of dwell times at nearside bus stops on the benefits of transit signal priority. The objective of the analysis was to test the hypothesis that longer dwell times would result in larger system-wide disbenefits given that a portion of the green time would be lost while waiting for the transit vehicle as it loads and unloads passengers at the bus stop.

Five levels of bus dwell times are simulated in this analysis that range from 5 to 60 seconds, as summarized in Table 5.1. Figure 5.29 clearly demonstrates, as would be expected, that the transit vehicles benefit from transit signal priority regardless of the duration of the dwell time. However, Figure 5.30 demonstrates that the system-wide disbenefits of transit signal priority increase as the dwell time increases. The increase in system-wide delays is attributed to two factors. First, because the roadway is a single lane, the general traffic approaching the signalized intersection has to queue behind the transit vehicle. Second, because the bus stop is located within the detection zone the signal timings are adjusted to allow the transit vehicle to proceed through the intersection, however, given that the transit vehicle is loading and unloading passengers a portion of the green time is lost with no utilization.

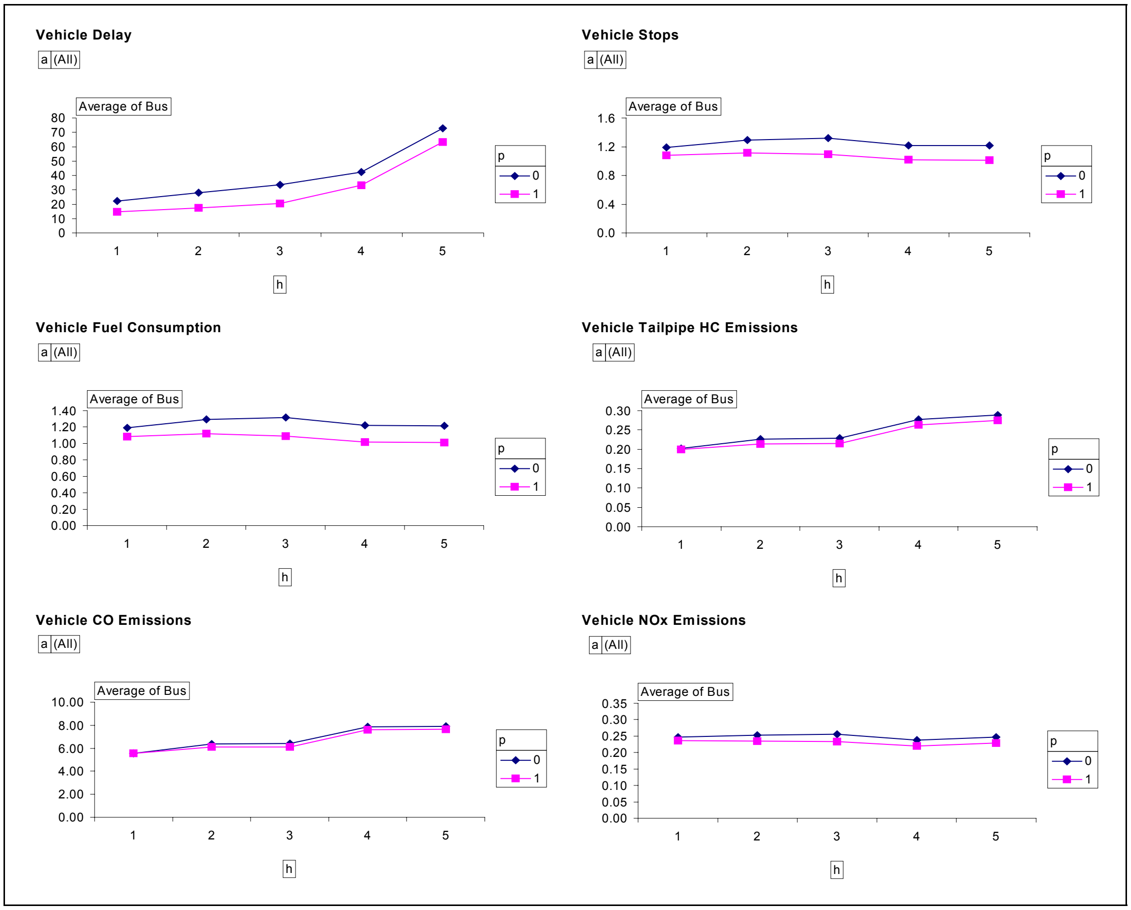


Figure 5.29: Variation Average Transit Vehicle Impacts of Transit Priority as a Function of Dwell Time (2-phase Signal Operation – Transit Demand of 12 veh/h)

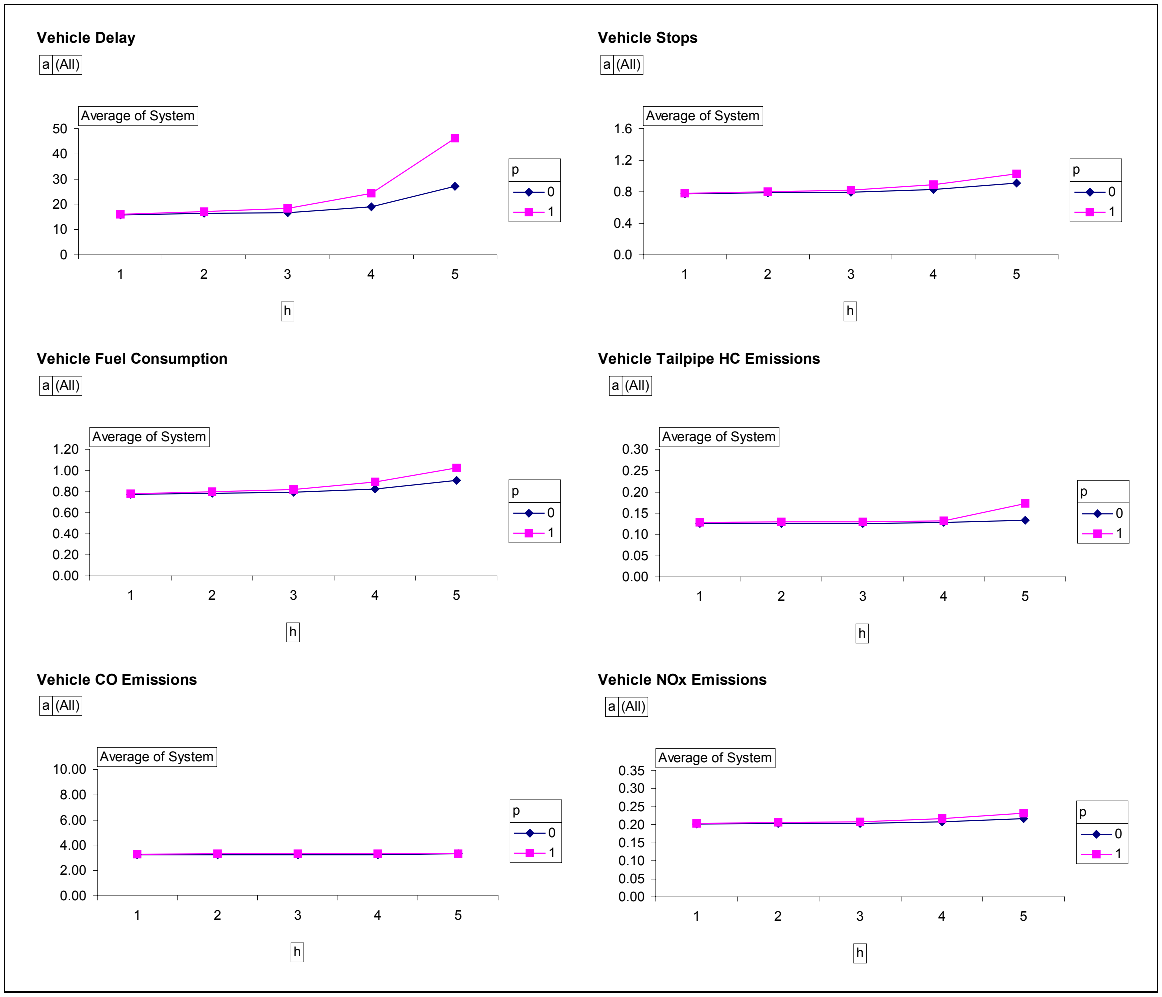


Figure 5.30: Variation Average System-wide Impacts of Transit Priority as a Function of Dwell Time (2-phase Signal Operation – Transit Demand of 12 veh/h)

5.4.7 Person-based Measures

Because of differences in vehicle ridership between automobiles and transit vehicles, it was important to compare the results in terms of person delay. In conducting the comparison the average occupancy of transit vehicles and automobiles was assumed to be 30 and 1.5, respectively. In all simulations, a total of 100 automobiles were simulated with the number of transit vehicles set to 1, 3, and 5 for a transit demand of 12, 36, and 60 veh/h, respectively.

Table 5.4 demonstrates a significant difference in vehicle versus person trips, especially for high transit vehicle demands. For example, in the case of an automobile demand of 1200 veh/h with a transit vehicle demand of 60 veh/h over a 5-minute simulation time horizon, an automobile to transit vehicle breakdown of 95.2 and 4.8 percent was observed. However, with the large discrepancy in ridership between transit and private vehicles, the 4.8 percent of vehicle trips associated with transit vehicles carries 50 percent of the total person trips, as demonstrated in Table 5.4.

Table 5.4: Comparison of Vehicle Percentage and Person Percentage

	# of Vehicles	Vehicle Percentage	Person Percentage
Private Vehicles	100	99.0%	83.3%
Transit Vehicles	1	1.0%	16.7%
Private Vehicles	100	97.1%	62.5%
Transit Vehicles	3	2.9%	37.5%
Private Vehicles	100	95.2%	50.0%
Transit Vehicles	5	4.8%	50.0%

Figure 5.31, 5.32 and 5.33 illustrate differences in vehicle and person delay estimates for the three transit vehicle demand levels that were considered. The figures clearly demonstrate that the benefits associated with transit signal priority increase with higher transit vehicle demands especially if transit vehicle ridership is significantly higher than automobile ridership. For example system-wide reductions in person delay range from 6 to 19 percent depending on the transit vehicle demand, while reductions in vehicle delay are only in the range of 1 to 5 percent, as demonstrated in Table 5.5. It should be noted at this point that the results that are presented in Table 5.5 reflect equal demands at the signalized approaches with a volume-to-capacity ratio in the range of 77 percent.

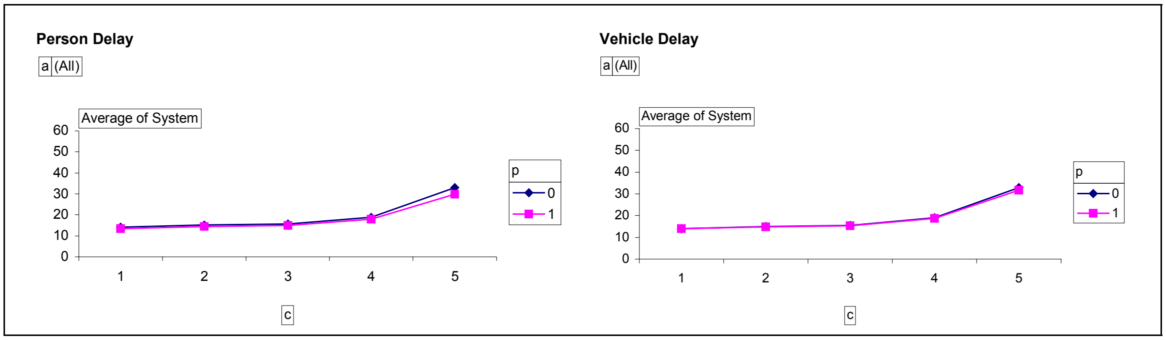


Figure 5.31: Comparison of Person-based Measures with Vehicle-base Measures: System-wide Impacts of Transit Priority (2-phase Signal Operation – Transit Demand of 12 veh/h)

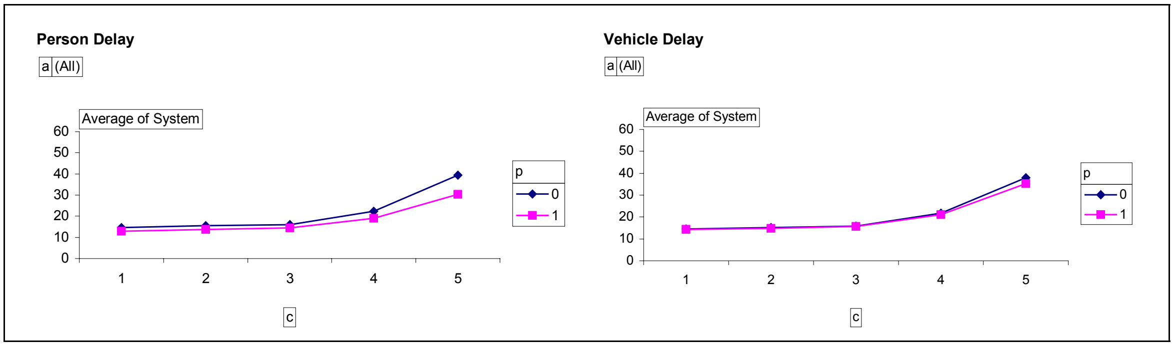


Figure 5.32: Comparison of Person-based Measures with Vehicle-base Measures: System-wide Impacts of Transit Priority (2-phase Signal Operation – Transit Demand of 36 veh/h)

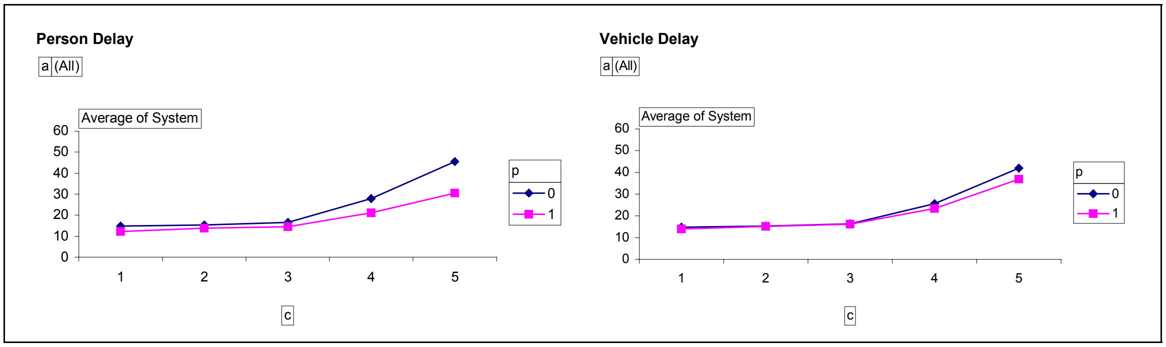


Figure 5.33: Comparison of Person-based Measures with Vehicle-base Measures: System-wide Impacts of Transit Priority (2-phase Signal Operation – Transit Demand of 60 veh/h)

Table 5.5: System-wide Delay Reduction by Transit Priority

Transit Demand (veh/h)	Delay Averaged by Person	Delay Averaged by Vehicle
12	5.7%	1.3%
36	14.1%	3.0%
60	19.4%	5.1%

By comparing the system-wide impacts of transit signal priority on person-delay, as illustrated Figure 5.34 through Figure 5.37 to the system-wide impacts on vehicle delay, as illustrated in Figure 5.19, 5.20, 5.22, and 5.23, it is evident that system-wide benefits are achievable especially if transit vehicle ridership is significantly higher than automobile ridership. Some general conclusions can be derived, as follows:

- Under certain instances (signal timings are sub-optimal or level of congestion is not high) transit signal priority can result in system-wide reductions in vehicle delay. In these cases significant reductions in person delay are achievable especially if transit vehicle ridership is significantly higher than automobile ridership.
- In most cases transit signal priority results in minor system-wide disbenefits in terms of vehicle delay. Significant differences in automobile and transit vehicle ridership can offset these increases in vehicle delay by introducing minor system-wide reductions in person delay. These benefits clearly depend on the transit demand and transit vehicle ridership.
- Under certain instances transit signal priority can result in significant system-wide increases in vehicle delay especially if priority is provided to minor approaches. In these cases the large differences in transit and automobile ridership cannot offset the system-wide disbenefits in vehicle delay.

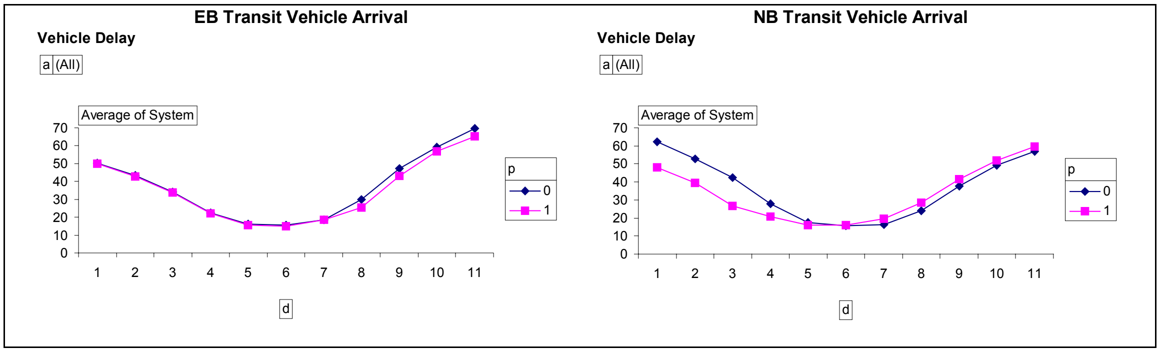


Figure 5.34: Person-based Transit Priority System-wide Benefits as a Function of Demand Distribution (2-Phase Signal Operation with 50:50 Split – Transit Demand of 12 veh/h)

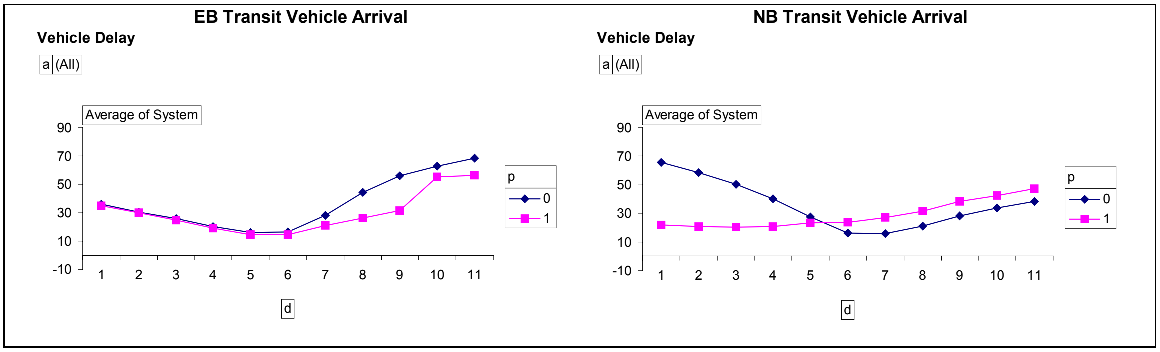


Figure 5.35: Person-based Transit Priority System-wide Benefits as a Function of Demand Distribution (2-Phase Signal Operation with 50:50 Split – Transit Demand of 60 veh/h)

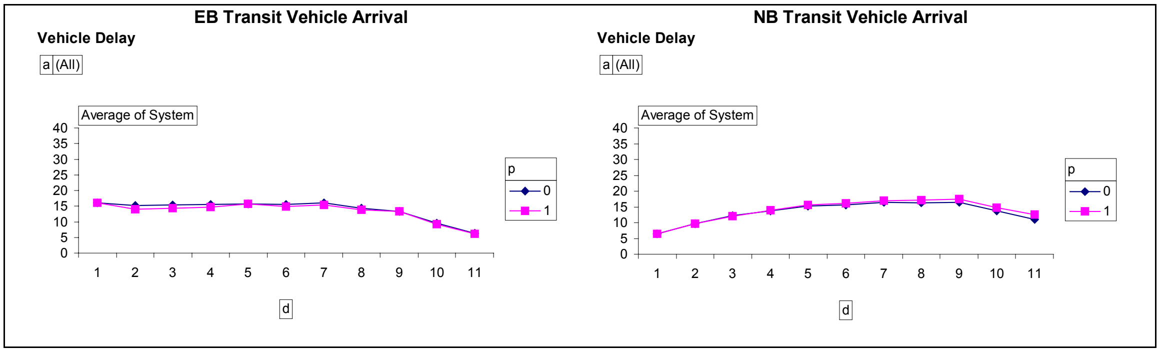


Figure 5.36: Person-based Transit Priority System-wide Benefits as a Function of Demand Distribution (2-Phase Signal Operation with Optimised Phase Split – Transit Demand of 12 veh/h)

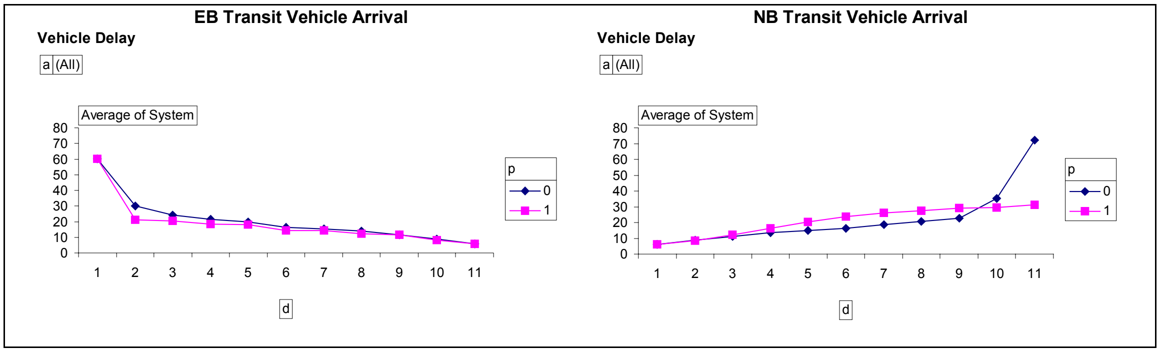


Figure 5.37: Person-based Transit Priority System-wide Benefits as a Function of Demand Distribution (2-Phase Signal Operation with Optimised Phase Split – Transit Demand of 60 veh/h)

5.5 Findings and Conclusions of the Study

The objective of this study was to conduct a systematic evaluation of transit signal priority on a simple isolated intersection in order to address a number of hypotheses. The conclusions of the study can be summarized as follows:

a. In general transit priority provides benefits to transit vehicles that receive priority. These benefits are highly dependent on the time of arrival of the transit vehicle within the cycle length and the phase of the traffic signal that is requesting priority.

b. Transit priority has a marginal system-wide impact for low traffic demands, however as the demand increases the system-wide disbenefits of transit priority increases.

c. The system-wide impact of transit priority is dependent on the frequency of transit vehicles. As the transit vehicle frequency increases larger system-wide disbenefits are observed.

d. Transit priority impacts are sensitive to the demand distribution at a signalized intersection. Transit vehicle arrivals on heavily congested approaches may result in system-wide benefits if the conflicting approaches are not congested. Alternatively, transit vehicle arrivals on lightly congested approaches may produce significant system-wide disbenefits if the conflicting approaches are heavily congested.

e. The system-wide benefits of transit priority are dependent on the phase at which the transit vehicles arrive especially if the cycle length is maintained within the priority logic. Transit vehicle arrivals during the early phases produce minimum disruptions to the general traffic while transit vehicle arrivals for the latter phases produce significant system-wide disbenefits.

f. The system-wide benefits of transit signal priority are highly dependent on the optimality of the base signal timings. Specifically, if the priority logic enhances the signal timings system-wide benefits can be achieved by virtue of improving the signal timings.

g. Transit vehicle dwell times at near-side bus stops can have significant system-wide impacts on the potential benefits of transit signal priority. Specifically, the system-wide disbenefits increase with an increase in bus dwell times if the bus stop is located within the detection range of the traffic signal.

6 CONCLUSIONS

6.1 Introduction

The main objective of thesis was to analyze the potential benefits of transit signal priority, adaptive signal control, and their interaction. The analysis is conducted on a section of the Columbia Pike that covers 21 signalized intersections. A modeling and field evaluation of the interaction of transit signal priority and SCOOT adaptive signal control is conducted. The modeling is achieved using the INTEGRATION microscopic simulation software. A direct comparison between simulation and field results was conducted in order to ensure consistency between the simulation and field environments. Five signal priority and six signal control scenarios were considered for both the AM peak and midday travel periods. The priority scenarios included:

- **Base Scenario:** No priority offered to any vehicle.
- **Priority Scenario 1:** Priority only to express buses traveling along Columbia Pike.
- **Priority Scenario 2:** Priority only to regular buses traveling along Columbia Pike.
- **Priority Scenario 3:** Priority to all buses traveling along Columbia Pike only.
- **Priority Scenario 4:** Priority to buses traveling on streets crossing Columbia Pike.
- **Priority Scenario 5:** Priority to all buses traveling along Columbia Pike and its cross-streets.

The adaptive signal control scenarios included:

Signal Scenario 1 – Fixed-time Control: Simulation of current MONARC fixed timing plans for all intersections along the corridor.

Signal Scenario 2 – Observed SCOOT Control: For SCOOT-controlled intersection, simulation of the average signal timings that were implemented by the SCOOT system at each intersection within a series of 15-minute intervals for other intersections, simulation of current MONARC fixed timing plans.

Signal Scenario 3 – INTEGRATION Split Control: Similar to Signal Scenario 1, but allows the phase split at all SCOOT-controlled intersections to be adjusted at 5-minute intervals by the signal optimization routine embedded within the INTEGRATION model.

Signal Scenario 4 – INTEGRATION Split and Offset Control: Similar to Signal Scenario 1, but allows the phase split at all SCOOT-controlled intersections to be adjusted at 5-minute intervals by the INTEGRATION signal optimization routines. The offset is optimized each cycle length to minimize a network-wide performance index.

Signal Scenario 5 – INTEGRATION Split and Cycle Control: Similar to Signal Scenario 1, but allows the phase split and signal cycle of all SCOOT-controlled intersections to be adjusted at 5-minute intervals by the INTEGRATION signal optimization routines (non-coordinated adaptive control).

Signal Scenario 6 – Full INTEGRATION Control: Simulates non-coordinated SCOOT control along the corridor by allowing the INTEGRATION signal optimization routines to adjust the signal cycle length, phase split and signal offset at all SCOOT-controlled intersections. Cycle length and phase splits are adjusted every 5 minutes, while offsets are adjusted every cycle length.

In each scenario, the approaching transit vehicles were detected within 100 meters of the signalized intersection. Following this detection, the transit priority logic then provided either a green extension or an early green recall to accommodate the approaching vehicle. Both the green extensions and early green recalls were determined using increments of 5 seconds subject to maintaining the same cycle length. Some minimum and maximum green interval constraints for each signal phase were also taken into consideration to avoid providing too large green extensions or early recalls.

Having conducted the study along Columbia Pike and having established the validity of the INTEGRATION model in replicating the field conditions. A systematic evaluation of the sensitivity of transit signal priority to traffic, transit, and signal timing factors was conducted using a simple isolated signalized intersection. The use of a small network was essential in order to isolate critical variables and identify their impacts on the potential benefits of transit signal priority.

6.2 Contributions of the Thesis

This thesis makes three major contributions. The first contribution is that the study validates the SCOOT adaptive signal control logic that is embedded in the INTEGRATION model. Specifically, the INTEGRATION findings were consistent with the field results along the Columbia Pike corridor. The second contribution of the thesis is that it is a first attempt at evaluating the dynamic integration of adaptive signal control and transit signal priority. The third and final contribution of the thesis is that it identifies a number of critical traffic, transit, and signal variables that are critical in the evaluation of transit signal priority.

6.3 Conclusions

Based on the simulation study that was conducted in this these, a number of conclusions have been identified, as follows:

- Adaptive signal control is generally very difficult to improve on optimum fixed-time signal control, especially when traffic conditions are relatively constant or the traffic flow approaches congestion. The lack of benefits in adaptive signal control is attributed to two factors. First, when traffic volumes are fairly constant, a fixed-time operation may already operate at optimality. Second, when congestion arises, there is an increased pressure to use the maximum allowable green time allocated to each phase, which then creates a virtual fixed-time operation.

- Prioritized vehicles can almost benefit from the priority schemes considered under any signal control alternative. It is also shown in the simulations that the benefits to the transit vehicles are typically obtained at the expense of the general traffic especially during congested periods. During off-peak conditions, which featured less traffic demand, providing priority to transit vehicles did not result in system-wide disbenefits. In these situations, the spare capacity at the signalized intersections provided an opportunity to provide transit vehicle priority logic without significantly disrupting the general traffic operations.

- The system-wide benefits of transit signal priority are highly dependent on the optimality of the base signal timings. Specifically, if the priority logic enhances the signal timings system-wide benefits can be achieved by virtue of improving the signal timings.

- Overall system-wide benefits could be obtained if the number of prioritized vehicles is kept low.

- Transit priority impacts are sensitive to the demand distribution at a signalized intersection. Transit vehicle arrivals on heavily congested approaches may result in system-wide benefits if the conflicting approaches are not congested. Alternatively, transit vehicle arrivals on lightly congested approaches may produce significant system-wide disbenefits if the conflicting approaches are heavily congested.

- The system-wide benefits of transit priority are dependent on the phase at which the transit vehicles arrive especially if the cycle length is maintained within the priority logic. Transit vehicle arrivals during the early phases produce minimum disruptions to the general traffic while transit vehicle arrivals for the latter phases produce significant system-wide disbenefits.

- Transit vehicle dwell times at near-side bus stops can have significant system-wide impacts on the potential benefits of transit signal priority. Specifically, the system-wide disbenefits increase with an increase in bus dwell times if the bus stop is located within the detection range of the traffic signal.

6.4 Recommendations

The thesis investigated the potential benefits of integrating transit signal priority with SCOOT adaptive signal control. Furthermore, the thesis presented a systematic evaluation of transit signal priority to isolate critical parameters associated with transit signal priority.

It should be pointed out that the results from this study should not be viewed as definite, but rather as a general assessment of the potential benefits of transit priority. In particular, the results of the study are subject to the limitations of the simulation models used to conduct the evaluation. In the analysis of Columbia Pike, although an effort has been made to include as many significant factors as possible, it was impossible to consider all possible factors that affect the benefits of providing priority to transit vehicles along a corridor. For example, the priority logic implemented in the analysis is simplified. Consequently, it is recommended that further studies be conducted, as follows:

- It is recommended that the study be conducted using a more complex logic providing conditional priority based on the occupancy of vehicles requesting priority of passage, the level of congestion at the signalized intersection and the degree to which the prioritized vehicle adheres to schedule.

- Further studies are required to investigate savings in person delay as opposed to savings in vehicle delays. In the test scenarios, the v/c ratios for total demands go from 0.53 up to 1.03.

- Further studies are required to test transit priority over multi-lane roadways, consider bus bays, and study the impact of far-side bus stops on the potential benefits of transit priority.

- Further studies are required to quantify the benefits integrating other transit vehicle preferential alternatives with transit priority. Examples of such alternatives would be bus lanes to bypass queues at approaches to signalized intersections.

- Further systematic analysis is required to look at issues related to traffic signal coordination and how the impacts of transit priority vary for a system of traffic signals.

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