INTEGRATING TRANSIT SIGNAL PRIORITY WITHIN ADAPTIVE TRAFFIC SIGNAL CONTROL SYSTEMS

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ABSTRACT

This paper develops a simulation approach for integrating transit signal priority within an adaptive traffic signal control system. The paper also presents the findings of a simulation study evaluating the potential benefits of providing preferential treatments to transit vehicles at signalized intersections along urban arterials within an adaptive traffic signal control system. The study uses a 21-intersection section of the Columbia Pike arterial, in Arlington, Virginia as an evaluation case study. Using the INTEGRATION microscopic traffic simulation model, traffic simulations are performed for scenarios replicating observed a.m., midday, and p.m. peak in mid-June traffic along the corridor. For each period, evaluations are conducted for scenarios considering no priority, priority only to express buses running along Columbia Pike and priority to all bus running along Columbia Pike. The priority logic considered in the study provides simple green extensions and green recalls upon detection of approaching buses. Three types of traffic signal control scenarios are further considered in the analyses. These include fixed-time control, adaptive splits, and adaptive splits and offsets. The simulation results indicate that buses typically benefit from transit signal priority under all types of traffic signal control while the general traffic incurs disbenefits. The results further indicate that while adaptive signal control does not necessarily negate all potential negative impacts on the general traffic, it does reduce these negative impacts. It is further concluded that transit priority can be successfully deployed along a coordinated arterial without significant detrimental impacts on the general traffic under various types of traffic signal control.

INTRODUCTION

In recent years there has been a growing interest in the use of transit signal priority to promote transit ridership and reduce urban congestion. Transit signal priority typically attempts to facilitate the movements of buses across signalized intersections through temporary traffic signal timing adjustments following the detection of an approaching bus. The two most common adjustments constitute green signal extensions and early green recalls. Green extensions are granted when a bus is expected to arrive a few seconds after the end of the green, while early green recalls are granted to accommodate buses that would arrive a few seconds before the start of the green or reduce their wait a signalized approach.

For transit operators, transit signal priority is a tool that has the potential of increasing transit ridership. Since delays incurred by buses at signalized intersections typically account for 10 to 20 percent of bus running times *(1)*, transit signal priority offers the potential for significant reductions in travel time. In essence, it is anticipated that the provision of faster transit service may entice motorists to switch their travel mode to transit vehicles. Transit signal priority also promotes transit utilization through improved service reliability. By providing priority only to buses that are behind schedule, transit priority allows for instance for a better control of arrival times at individual stops, improved service regularity, and ultimately, increased positive perception of the transit service. Transit priority can also help reduce operating costs and staffing requirements, as reductions in bus travel times may allow a given level of service to be offered with fewer vehicles. Reductions in bus running times and number of stops may also reduce vehicle wear and tear, and consequently lead to an ability to defer vehicle maintenance and new vehicle purchases over longer time periods.

While numerous studies have already demonstrated the potential benefits of transit signal priority *(2, 3)*, deployments have been relatively slow in the United States. In 2002, there were for instance only 36 agencies who reported using transit priority *(4)*. In particular, very few deployments have been made along urban arterials with coordinated traffic signal operations. While benefits have been demonstrated for transit operations, studies have also shown potential negative impacts on traffic on streets crossing the bus routes, particularly at intersections with high traffic. Traffic engineers are also often reluctant to approve the deployment of transit signal priority along arterials due to fear that the priority measures may disrupt traffic progression patterns by accommodating for the slower traveling transit vehicles, thus causing increased congestion and safety risks.

To date, evaluations of transit signal priority deployments along arterials have typically only considered facilities controlled by fixed-time signals *(5, 6)*, which are the most sensitive to transit signal priority. Since fixed-time control typically implements timings developed off-line and reflecting historically observed average traffic conditions, it does not provide an automatic capability for signal timing adjustments in response to changes in traffic conditions caused by transit preferential measures. While fixed-time control is common in North America, there has been a growing interest in adaptive traffic signal control systems, particularly in Europe and Asia. Well-known examples of such systems include the SCOOT and SCATS real-time traffic signal control systems, which are collectively in operation in more than 200 cities around the world, but only six in North America. By having the capability to alter the signal timings in response to detected changes in traffic conditions, these systems can theoretically reduce the potential for negative traffic impacts on the general traffic that arise from the use of transit signal priority.

Starting from a previous study that used the Columbia Pike arterial in Arlington, Virginia to evaluate the effectiveness of providing transit signal priority within a fixed-time coordinated signalized urban arterial *(6)*, this paper presents the results of a simulation study that utilizes the same arterial to evaluate the potential benefits of transit priority within traffic-adaptive signal control. This study looks more specifically at the incremental benefits that advanced traffic signal control systems may provide along urban arterials to reduce the potential negative impacts of transit signal priority deployments. The paper starts with a brief review of transit priority deployments and evaluations. This is followed by a presentation of the main characteristics of the selected study corridor and of the simulation modeling used to conduct the evaluations. The transit signal priority strategy and scenarios considered for the study are then described, followed by the simulation results and main conclusions.

LITTERATURE REVIEW

Despite an interest in transit signal priority dating back to the 1970s, there are only few documents describing field system deployments *(3, 7)*. The vast majority of the literature simply reports on simulation evaluations *(2)*. Simulations allow evaluations to be made without having to commit to costly field deployments. Typical performance measures that are considered include changes in bus travel times, bus intersection delay, average vehicle delay, average vehicle stops, average person delay and average person stops. Other measures also include percentage of priority calls granted and used as intended, increase in schedule adherence, and improvement in arrival time reliability.

Studies performed to date generally indicate that buses benefit from signal priority systems. Field evaluations reported in Chang et al. *(2)* and Collura et al. *(7)* indicate reductions in average intersection bus delays ranging between six to 42 percent, and reductions in average bus travel times ranging between zero and 38 percent. Some studies also found that vehicles traveling on the same approaches as the buses receiving priority may also occasionally indirectly benefit from transit priority. Other potential transit benefits identified in the literature include improved transit schedule reliability, increased passenger comfort, reduced fuel consumption and emissions, reduced equipment wear and tear, and ultimately, increased attractiveness of the transit service.

The potential adverse impacts of transit signal priority are increased delays and queue lengths for vehicles traveling on cross-streets. Increased stops and delays to the general traffic may also result from the disruption of traffic progression patterns along coordinated arterials *(8)*. While a number of deployments produced no significant impacts on the general traffic, others yielded stops and delay increases as high as 23 percent *(2, 7)*. From a safety standpoint, it has also been argued that red truncation and the use of more advanced features such as phase skipping could confuse motorists and increase accident risk. Despite these negative elements, a frequent perception is that transit signal priority may be implemented in an area without significant negative impacts on the general traffic if the preferential measures are tailored for the area and developed with the needs of the entire traffic in mind *(9)*. Another important understanding is that benefits will often be intimately linked with the characteristics of each deployment site *(10)*.

As indicated earlier, most of the evaluations reported in the literature are for systems deployed within fixed-time traffic control systems. The few evaluations that have looked at deployments within adaptive systems *(2, 11, 12)* generally provide similar conclusions in terms of potential benefits to transit vehicles and negative traffic impacts. In one example, a simulation of transit priority along a 7-intersection arterial controlled with a SCOOT system demonstrated a potential to reduce intersection delay by 22 percent for transit riders at the expense of a 5 percent delay increase to persons traveling in cars with respect to optimal adaptive control without bus priority *(12)*. In this case, however, quicker recoveries and reduced overall negative impacts may be expected due to the adaptive nature of the traffic signal control system.

STUDY CORRIDOR

The study uses the Columbia Pike arterial that runs through Arlington County in the Northern Virginia section of the Washington, D.C. region as a test corridor. This arterial is a major east-west traffic corridor that carries an average of 26,000 vehicles per day. It serves large federal agencies (Pentagon and Navy Annex) at its eastern end, and links residential and medium-density retail business neighborhoods. It also exhibits the highest ridership of any bus corridor in Virginia with over 9,000 transit daily trips.

Geometric Considerations

As shown in Figure 1, the study corridor extends over 6.35 km (3.95 mi) and covers 20 signalized intersections and one freeway type interchange. Of these intersections, those with Carlin Spring, George Mason, Glebe, Walter Reed, Washington and Joyce carry significant cross-street traffic. A pedestrian traffic signal is also located in front of the Navy Annex. The corridor further features a relatively straight alignment, with only one 90 degree curve (not shown in Figure 1) before the intersection with Joyce, as well as grades exceeding 4 percent on some sections.

Traffic Conditions

Traffic flows along the corridor are directional during peak periods and more balanced in off-peak periods. During the AM peak (6:00 – 9:00 a.m.), traffic along Columbia Pike generally moves eastward, towards the Pentagon and downtown Washington, while cross-street traffic generally travel northbound. During the afternoon peak (3:30 - 7:00 p.m.), motorists returning home typically create opposite trends. Traffic also exhibits day-to-day fluctuations of up to 20 percent within any given 15 min intervals. Such variations are thus likely to create uncertainty in the potential benefits and impacts that may result from the deployment of transit signal priority along the corridor.

Signal Operations

Traffic movements between Dinwiddie and Courthouse are normally controlled by a SCOOT real-time signal control system while other intersections are operated with time-of-day fixed-time control. For this study, however, various signal control alternatives are considered for the section of the corridor extending between Dinwiddie and Courthouse, as described later in the paper.

Transit Operations

Figure 2 illustrates the bus routes serving the corridor and the location of bus stops along both the arterial and cross-streets. The figure also distinguishes between curbside stops, stops with exclusive bus bays, and stops requiring buses to use the right-turn lane. This categorization is important as different bus stop geometries result in different degrees of interactions between traffic and transit operations. The figure further categorizes the stops according to their relative position to the intersections, showing a mix of far-side, near-side and mid-block stops. This adds to the complexity of the evaluation, as different stop locations will not have the same requirements in terms of transit signal priority. For instance, dwell times must be accounted for when considering near-side stops, but not with far-side stops.

SIMULATION MODEL SETUP

The INTEGRATION microscopic traffic simulation model *(13)* was used to conduct the evaluations. This model was conceived as an integrated simulation and traffic assignment model and has the ability to track the movement of individual vehicles every 1/10th of a second. It further allows for the outputting of details tracking information about the movement of individual vehicles, which is a valuable feature for analyzing the effectiveness of transit signal priority actions. In addition to estimating stops and delays, the model also applies second-by-second microscopic vehicle fuel consumption and emission models to estimate the total fuel consumed and emissions produced by individual vehicles.

For the network modeling, information on link length, grade, number of lanes, lane striping, free-flow speed, speed/flow relationship, and saturation flow rate were provided for each coded link. Most of the code information was derived from field data, except for the saturation flows, which were assumed to correspond to an ideal 1900 vehicles/hour to reflect the high geometric design of the study corridor. Free-flow speeds ranging between 65 and 70 km/h (40 and 45 mph) were further coded despite posted speed limits of 48 and 56 km/h (30 and 35 mph) to reflect GPS-measured observed speeds along the corridor.

To account for temporal variations, the traffic demand was modeled using 15 min intervals. For each interval, the demand was expressed in the form of an origin-destination matrix that was calibrated to minimize the relative errors between the observed and simulated link flows. These matrices were generated based on traffic flow data from loop detectors installed along the SCOOT-controlled section of the corridor and additional manual vehicle counts that were conducted at a number of key intersections to obtain information about turning percentages. The manual traffic counts were necessary because turning percentages could not be estimated from the SCOOT loop detectors due to their placement at the upstream end of intersection approaches.

Transit operations were finally modeled so that bus arrivals at key transit stops corresponded to published schedules. Based on field measurements, transit dwell times were further assumed to be randomly distributed with a 15 s average service time and a 10 percent coefficient of variation. In this case, while it is expected that buses would attempt to stay on schedule, the combined impacts of variable dwell times and potential delays caused by surrounding traffic operations makes it impossible to assume that a bus would reach a given intersection at exactly the same point within a signal cycle.

TRANSIT PRIORITY LOGIC

The transit priority logic in version 2.30 g of the INTEGRATION model attempts to replicate the actions of signal priority systems considering green signal extensions and early green recalls:

- Approaching buses are detected at a user-specified distance upstream of the signal stop line. In this case, the distance was set at 100 m (328 ft).
- If a bus is to enter the intersection during the green interval, no signal alteration is made.
- If a bus is to arrive after the end of the green, the green is extended at increments of *n* seconds until either the vehicle has left the approach or the maximum green is reached. The time required for the extensions is taken from the next phases in the cycle that has not been reduced to its minimum allowed duration.
- If a bus is detected while traffic another approach is being served, the active green phase is terminated after an increment of *n* seconds, or as soon as the minimum green time is satisfied, to allocate service to the approaching bus as quickly as possible. The green is returned to the prioritized approach only after having satisfied the minimum green, amber, and all-red intervals of all the intermediate phases in the phase sequence. Following the early green recall, the green time on the prioritized approach is terminated at its normal end point.
- If a priority request has already been granted during the signal cycle, no additional changes are made to the signal timings for the remainder of the cycle to minimize traffic disruption.
- Priority requests are granted on a first-come first-serve basis. In the highly unlikely event that two or more requests are received at the same instant in time from conflicting approaches, no changes are made since there is no means to prioritize the priority requests.

This logic is further subject to the four following constraints:

- Service of minimum green times assigned to each phase.
- Extensions cannot result in green phases exceeding their maximum defined duration.
- Cycle length is fixed in order to preserve coordination with adjacent intersections.
- No phase skipping while transitioning to and from a priority phase.

Based on the above constraints, Equation 1 is used to determine the maximum allowed duration of a prioritized green phase. The maximum green is the time that remains within a signal cycle after subtracting all intergreen intervals and the specified minimum greens of all conflicting phases.

$$ge_{\max i} = \min\left(\mathrm{g}_{\max i} \;;\; \mathrm{C} - \mathrm{a}_{\mathrm{i}} - \sum_{\mathrm{j}=1}^{\mathrm{n}} \left(\mathrm{g}_{\min \mathrm{j}} + a_j \right) \text{ for all } \mathrm{j} \neq \mathrm{i} \right) \qquad [1]$$

where: $ge_{max\,i}$ = Maximum allowed duration of phase i,
$g_{max\,i}$ = User-defined maximum green for phase i,
$g_{min\,j}$ = User-defined minimum green for phase j,
C = Cycle length,
a_j = Intergreen duration at end of phase j, and
n = Number of phases within signal cycle.

While the INTEGRATION model does not explicitly consider pedestrians, minimum pedestrian crossing times can easily be considered by setting the minimum green phase durations to correspond to the minimum time required by pedestrians to cross the roadway. In such a case, the longer minimum green times would reduce the maximum allowable green time for each phase, and thus, the magnitude of green extensions or early recalls that could be granted.

The assumption that simultaneous conflicting priority requests result in no priority addresses the difficulties of handling such cases. Currently, priorities are typically granted on a first-arrived first-served basis. While this may not be the best solution, the determination of the ideal actions to resolve conflicting requests is a problem that has varying solutions depending of the information that is assumed available. For instance, priority could be given to the vehicle having the highest occupancy or the farthest behind schedule. This requires either real-time knowledge of transit ridership near each intersection or the capability to compare arrival times to scheduled arrival times in real-time. Such sophisticated systems are not available on the streets.

Another element not considered is the impact of higher priority calls from emergency vehicles allowing them to override the signal operation, including any transit priority measure in operation. While the objective of transit priority is to balance benefits to transit vehicles against potential impacts on traffic, emergency signal preemption is only concerned about providing benefits to the emergency vehicles. Basic safety concerns generally lead to the requirement that amber signals be displayed when preempting a green signal. However, research is still needed to determine the implications of non-anticipated terminations of priority measures on transit vehicle drivers. While drivers may be aware that priority measures are provided to their vehicle, this does not necessarily mean that every vehicles obtains priority at all intersections. Constraints on such priority operations require further research such as maximum allowable green extensions and compensation measures preventing priority to be granted in a number of cycles following a granted request.

EVALUATION SCENARIOS

For the study, three evaluation periods are considered:

- **AM Peak:** 7:00 a.m. to 9:00 a.m., eastbound and northbound flows
- **Midday Traffic:** 11:00 a.m. to 1:00 p.m., balanced flows
- **PM Peak:** 4:30 p.m. to 6:30 p.m., westbound and southbound flows

Table 1 indicates the number of vehicles being simulated within each evaluation period, the distance traveled by each vehicle class, and the assumed average vehicle occupancy. It can be noted that express buses did not run during the midday period, thus leaving only two scenarios for this period. For the passenger vehicles, an average vehicle occupancy of 1.2 persons was utilized, while average bus occupancies of 16 and 23 passengers were considered for the various periods based on field observations.

For each period, three priority scenarios are considered for the section of Columbia Pike extending between Dinwiddie and Quinn:

- **Base**: No priority.
- **Express bus only**: Priority to express buses traveling along Columbia Pike (Route 16J).
- **Columbia Pike routes**: Priority to regular and express buses traveling along Columbia Pike (Routes 16 and 24)

In each case, a default green extension interval of 2 s is used based on an earlier analysis *(6)*. A 5 s minimum green time is also used for all phases to impose minimum constraints on the priority logic.

In addition to the priority scenarios, the following signal control scenarios are further considered:

- **Fixed-Time**: Use of fixed-time plans provided by the Department of Public Works of Arlington County and that were developed less than a year before the study.
- **Adaptive Splits**: Implementation of offsets and cycle time from the fixed-time plans, but with splits adjustments performed every 5 min by INTEGRATION based on observed traffic.
- **Adaptive Splits and Offsets**: Split adjustments every 5 min with offset adjustments every cycle based on observed traffic.

The INTEGRATION signal optimization routines were designed to provide signal control logic similar in philosophy to SCOOT. The routines adjust the cycle length, green split and signal offset of individual intersections at regular intervals to match observed traffic demands. The cycle length and green split are determined using the optimization technique described in the Canadian Capacity Guide for Signalized Intersections *(14)*, which implement the Webster-Cobbe signal optimization method. This method determines the green split and cycle length of individual intersections by analyzing the arrival and departure flows on each intersection approach on a lane-by-lane basis. Equations 2 to 4 are first used to determine the cycle length of each intersection. However, contrary to SCOOT, which allows the cycle of a critical intersection within a group to be used as the common cycle length, INTEGRATION only considers signalized intersection on an individual basis. Nevertheless, this approach is consistent with observed SCOOT control along the study corridor, which typically implemented constant signal cycles matching the cycles in use at the fixed-time signals bordering the real-time controlled section (105 s during peak periods and 75 s during off-peak periods).

$$y_i = \frac{q_i}{S_i} \qquad [2]$$

$$Y = \sum_j y_{ij} = \sum_j \frac{q_{ij}}{S_{ij}} \qquad [3]$$

$$C_{opt} = \frac{1.5L + 5}{1 - Y} \qquad [4]$$

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 length (seconds).

Following the determination of the optimal cycle, Equations 5 and 6 are used 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.

$$\sum g_j = C_{opt} - \sum_j I_j \qquad [5]$$

$$g_j = \sum g_j \cdot \frac{y_j}{Y} \qquad [6]$$

where:

$_j$ = Green interval for phase *j* (seconds),
I_j = Intergreen period following phase *j* (seconds).

At the end of the process, the ideal signal offset for each intersection is determined by minimizing a performance index function that is a combination of stops and delay and using a cyclic flow profile approach similar to TRANSYT-7F and SCOOT.

To account for the stochastic nature of the traffic simulation, 30 two-hour simulation runs were finally conducted for each scenario. Within each run, performance measures were compiled on person travel time, person delay, vehicle stops, vehicle fuel consumption, and vehicle emissions. In this case, person-based statistics were compiled to reflect the fact that transit priority systems are usually deployed to promote transit ridership and the efficient movements of persons rather than vehicles. Vehicle fuel consumption is further considered due to its link to vehicle operating costs, while vehicle emissions are considered to assess the potential environmental impacts of the various strategies considered.

SIMULATION RESULTS

Priority under Fixed-Time Control

Table 2 summarizes the impacts of transit signal priority under fixed-time control. In this case, it is first observed that buses receiving priority generally benefit from the preferential treatments, although at a relatively small scale. When only express buses receive priority, average delay reductions of 4.2 and 3.4 percent are obtained for the AM and PM peaks, respectively. These reductions translate into travel time reductions of only 12 to 20 s per vehicle over the length of the corridor. Reductions in the number of stops, fuel consumption and vehicle emissions are also observed, although not always at a statistically significant level. Benefits for transit operations are again observed when priority is provided to all buses traveling along Columbia Pike. Depending on the evaluation period, the observed delay reductions vary between 3.1 percent and 5.6 percent, yielding a maximum travel time reduction of almost 30 s. The impacts on stops, fuel consumption and emissions vary between a 0.8 percent increase and a 3.0 percent decrease, again with many differences lacking statistical significance.

For the general traffic, transit signal priority resulted in negligible impacts. In the AM peak, the provision of priority to all buses running along Columbia Pike resulted in a 5 percent increase in delays for the arterial traffic in the peak travel direction, a 2.4 percent increase for vehicles in the opposing direction, and a 2.3 percent increase for vehicles on the cross-streets. Small increases in the number of stops, fuel consumption, and emissions ranging between 0 and 1.0 percent are also observed for the various traffic groups, with the greatest impacts for the eastbound traffic. It is interesting to note that the most negatively impacted group here is the traffic traveling in the direction of travel that corresponds to the majority of buses receiving priority. This is attributed to changes in the established progression patterns caused by the priority requests. In particular, it can be considered that vehicles benefiting from an early green will typically reach the next intersection ahead of the bus. Since these vehicles may then arrive at the next intersection earlier than expected, additional delays and longer queues are not surprisingly incurred there.

For the Midday and PM peak periods, transit signal priority does not appear to affect traffic operations. While the general traffic seems to slightly benefit during the PM peak period when priority is given only to the express buses, the observed impacts generally remain statistically insignificant. However, contrary to the AM peak, it is observed that vehicles traveling westbound in the same direction as the express buses appear to benefit from the transit signal priority. While the observed changes are not significant, this trend may be explained by the fact that the traffic signal progression pattern during the PM peak may be less sensitive to signal timing alterations.

Impact of Adaptive Control on Traffic Performance

Before analyzing the impacts of transit priority within adaptive control, the effects of switching from a fixed-time to a traffic-adaptive system must be analyzed to ensure that any observed impacts resulting from the change in traffic control are not unduly attributed to the introduction of transit signal priority. As can be observed in Table 3, the switch to adaptive control generally benefits traffic operations. However, the benefits remain relatively small, with overall changes in performance measures remaining below 5 percent. These small benefits are explained by the repetitive nature of traffic patterns along the corridor. Since fixed-time signals control the traffic movements at both end of the corridor under all signal control scenarios, these signals thus tend to create repetitive traffic arrival patterns along the corridor. As a result of this repetitiveness, the adaptive control systems then generally tend to replicate the fixed-time signal timing parameters. For the AM and PM peaks, the presence of high traffic volumes also reduces the ability to alter the signal timings.

Another observation from Table 3 is that the switch to adaptive split and offset control typically results in slight increases in delays and number of stops for both the AM peak and Midday periods for the general traffic. These results are not surprising as experience with adaptive control systems suggests that these systems do not always reduce stops and delays, particularly in periods of high demands or where traffic performance is linked to the ability to tailor progression patterns. In Table 3, it can further be observed that benefits for one traffic group are typically obtained at the expense of other traffic groups. This is a normal consequence of switching the green time around. In most cases, the inability to obtain overall positive impacts can be traced to the difficulty of optimizing green times at intersections with high cross-street flows. Here, the need to consider high traffic flows from both the arterial and cross-street approaches may prevent the signal timing optimization algorithms to select truly optimal offsets, thus potentially causing the observed increases in stops and delays.

Transit Priority under Adaptive Split Control

The first half of Table 4 indicates that the provision of preferential treatments generally benefits transit operations under adaptive traffic signal split control. However, it can be observed that the benefits obtained are typically smaller than under fixed-time control. For instance, while express buses experienced delay reductions of up to 4.2 percent under fixed-time control, they experience delay reductions of only up to 2.6 percent, or 12 s, under adaptive split control. In this case, the reduction in benefits cannot be attributed to reduced delays in the reference scenario used for comparisons, as a comparison of Tables 2 and 4 indicates slightly higher delays for buses in the adaptive split scenario without priority compared to the fixed-time scenario without priority. Reduced stops, fuel consumption and emissions are also obtained for the AM peak, but again on a smaller scale than under fixed-time control. For the PM peak, negligible reductions in stops and fuel consumption are further accompanied by negligible increases in vehicle emissions. When priority is expanded to all buses along Columbia Pike, no clear trends are observed when compared to fixed-time control. In this case, transit priority results in slightly increased benefits for buses during the AM peak, and slightly reduced benefits for both the Midday and PM peak periods.

In terms of traffic impacts, the simulation results indicate again a trend towards negative impacts. For the AM peak, transit priority resulted in a 4.4 percent increase in delay, a 0.9 percent increase in the number of stops, and increases in fuel consumption and emissions ranging between 0 and 0.7 percent. In particular, increases in performance measures are observed for all travel directions. This indicates that no clear benefits are necessarily derived from traveling on the same approaches as the buses receiving preferential treatments. For the Midday and PM peak period there are generally no noticeable impacts. However, while the reported traffic impacts are in this case generally similar to those listed in Table 2 for transit priority with fixed-time control, a slight but likely non-significant reduction in negative impacts can be noted.

Transit Priority under Adaptive Split-Offset Control

Data on the second half of Table 4 presents the simulation results for transit priority within adaptive green split and offset control. As shown earlier in Table 2, this scenario resulted in a slight deterioration in general traffic performance. From the standpoint of transit operations, buses are again found to benefit from the priority, with statistically significant reductions in delays ranging from 2.9 to 7.4 percent. While small increases in vehicle stops, fuel consumption and vehicle emissions are also observed, these increases remain relatively small (less than 0.5 percent) and typically statistically insignificant. When compared to the previous control scenarios, no clear trends can be identified from the switch to a more advanced traffic control system, because in some instances small reductions in performance measures are observed while in other cases slight increases are observed depending on the evaluation period.

In terms of traffic operations, negative impacts are again generally observed for the AM peak, with a 2.7 percent increase in traffic delays when priority is given to all buses running along Columbia Pike. Similarly to the previous control scenarios, no significant impacts are again typically observed for the Midday and PM peak periods, with the exception of a small increase in delays (0.9 percent) over the PM peak when priority is provided to all Columbia Pike buses.

For the AM peak, the negative impacts on traffic within the current scenario further appear to be less than for the two preceding scenarios. In particular, it can be observed that the negative impacts on the AM peak traffic are at their greatest under the fixed-time control scenario, reduced under the adaptive split control scenario, and further reduced under the adaptive split and offset scenario. A statistical analysis of the observed changes in overall traffic performance over the three signal control scenarios further reveal that these changes are generally statistically significant. This clearly points to a positive impact from integrating transit priority with advanced traffic signal control. However, similar observations cannot be made for the Midday and PM peak periods given the relatively small scale of the observed impacts in both scenarios.

CONCLUSIONS

The conclusions of the study can be summarized as follows:

- Buses generally benefit from the deployment of transit signal priority regardless of the type of traffic signal control within which transit priority is considered.
- There are no definite advantages for transit vehicles in integrating transit signal priority and adaptive traffic signal control systems. Specifically, greater benefits were obtained by the prioritized buses under adaptive control when priority was offered only to the express buses, but not when priority was offered to all buses running along the study arterial.
- The general traffic is typically negatively impacted by the deployment of transit signal priority under all types of traffic signal control. However, reduced negative impacts on traffic can be expected from the ability of adaptive traffic signal control systems to automatically adjust the signal timings to observed traffic conditions.
- The negative impacts of transit signal priority appear to be localized. Consequently, there is a potential for transit signal priority to be successfully deployed along coordinated arterials.
- The benefits provided by transit signal priority depend heavily on the traffic flow characteristics and the traffic signal control strategy in operation along the corridor under consideration. This is exemplified in the study by the different overall impacts obtained for the AM peak, Midday and PM peak periods.

By far the most important finding is that the negative impacts of transit signal priority on the general traffic can be mitigated with introduction of adaptive traffic signal control. While only small benefits were obtained for transit vehicles within the study, evaluations should be carried out on other arterials to determine whether these results are typical for coordinated arterials. In particular, evaluations should be conducted to determine the impacts of traffic and roadway characteristics on the performance and effectiveness of transit signal priority systems. Of particular interest would be to evaluate the incremental benefits that could be obtained under a full SCOOT control and alternative real-time systems. Evaluations under semi-adaptive and fully adaptive traffic signal control should also be investigated, as this type of traffic signal control is becoming more common. Additional research is also warranted to evaluate the incremental benefits provided by the use of more complex and context-sensitive priority logic that could be made possible by emerging technologies, such as logic providing priority only to buses that are behind schedule, only to buses carrying a certain number of passengers, or only when traffic conditions at an intersection indicate a low probability of significant traffic impacts.

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TABLE 1 Simulation Summary Statistics

Measure	Simulated Vehicles	Traveled Distance (km)	Occupancy (pers/veh)
AM Peak Period			
Express Buses	9	65	23
Regular Buses	56	304	23
Cross-Street Buses	39	36	23
Cars	25,092	37,042	1.2
Midday Period			
Express Buses	0	0	16
Regular Buses	21	132	16
Cross-Street Buses	27	25	16
Cars	21,421	30,311	1.2
PM Peak Period			
Express Buses	11	78	23
Regular Buses	51	257	23
Cross-Street Buses	42	38	23
Cars	24,655	41,346	1.2

TABLE 2 Impacts of Transit Signal Priority under Fixed-Time Traffic Signal Control

Performance Measure	Priority Scenario	Impacts on Traffic Groups					
		Fixed Time Control					
		Express Buses	Columbia Buses	EB Traffic	WB Traffic	Cross-Street Traffic	All Traffic
		AM Peak					
Travel Time (s/veh)	None	843.6	727.2	694.0	725.7	41.7	145.9
	Express	-2.4%	0.5%	0.0%	0.0%	0.2%	0.0%
	Arterial	-1.0%	-3.3%	2.4%	1.1%	1.4%	2.1%
Delays (s/veh)	None	480.5	439.7	337.5	325.1	26.6	67.2
	Express	-4.2%	0.9%	0.1%	0.0%	0.3%	0.0%
	Arterial	-1.8%	-5.5%	5.0%	2.4%	2.3%	4.5%
Stops (stops/veh)	None	21.27	18.99	15.21	15.21	0.91	2.61
	Express	-0.9%	-0.1%	0.0%	-0.2%	0.0%	0.0%
	Arterial	0.1%	-1.0%	1.0%	0.3%	0.4%	1.0%
Fuel (L/km)	None	0.144	0.154	0.289	0.116	0.083	0.110
	Express	-1.3%	0.1%	0.0%	0.0%	0.1%	0.0%
	Arterial	-0.5%	-1.4%	1.0%	0.2%	1.4%	0.8%
HC (g/km)	None	0.036	0.036	0.079	0.031	0.021	0.030
	Express	-1.9%	-0.4%	0.0%	0.1%	0.1%	0.1%
	Arterial	0.2%	-1.2%	0.0%	0.1%	0.7%	0.2%
CO (g/km)	None	1.198	1.202	2.380	0.920	0.539	0.877
	Express	-2.6%	-0.7%	0.0%	0.1%	0.1%	0.1%
	Arterial	0.2%	-1.2%	-0.3%	0.1%	0.7%	0.0%
NOx (g/km)	None	0.105	0.106	0.244	0.102	0.068	0.097
	Express	-0.8%	0.1%	0.0%	0.1%	0.0%	0.0%
	Arterial	-0.6%	-0.7%	0.1%	0.0%	0.4%	0.1%
		Midday					
Travel Time (s/veh)	None		814.0	626.5	693.0	31.9	122.6
	Express		0.1%	0.0%	0.1%	0.0%	0.0%
	Arterial		-3.5%	-0.4%	-0.1%	0.4%	-0.1%
Delays (s/veh)	None		508.7	285.9	326.4	16.8	49.6
	Express		0.2%	0.1%	0.1%	0.0%	0.0%
	Arterial		-5.6%	-0.9%	-0.2%	0.7%	-0.1%
Stops (stops/veh)	None		21.09	14.71	15.93	0.86	2.41
	Express		0.0%	-0.1%	0.0%	0.0%	0.0%
	Arterial		-0.4%	-0.3%	-0.4%	0.1%	-0.1%
Fuel (L/km)	None		0.157	0.160	0.161	0.061	0.107
	Express		0.0%	0.0%	0.0%	0.0%	0.0%
	Arterial		-1.3%	-0.2%	0.0%	0.1%	0.0%
HC (g/km)	None		0.040	0.048	0.048	0.017	0.031
	Express		0.0%	0.0%	0.0%	0.0%	0.0%
	Arterial		-1.1%	0.0%	0.0%	0.1%	0.0%
CO (g/km)	None		1.356	1.516	1.530	0.450	0.967
	Express		0.0%	0.0%	0.0%	0.0%	0.0%
	Arterial		-1.0%	0.0%	0.0%	0.0%	0.0%
NOx (g/km)	None		0.108	0.141	0.144	0.056	0.098
	Express		0.0%	0.0%	0.0%	0.0%	0.0%
	Arterial		-0.7%	0.0%	0.0%	0.0%	0.0%
		PM Peak					
Travel Time (s/veh)	None	745.4	610.4	719.2	813.1	31.5	167.1
	Express	-1.6%	-0.1%	0.1%	-0.4%	-0.4%	-0.3%
	Arterial	-1.4%	-1.7%	0.1%	0.0%	0.2%	0.1%
Delays (s/veh)	None	358.9	341.3	164.5	425.5	16.2	77.2
	Express	-3.4%	-0.2%	0.5%	-0.7%	-0.8%	-0.5%
	Arterial	-3.0%	-3.1%	0.6%	0.0%	0.3%	0.2%
Stops (stops/veh)	None	18.47	16.84	9.81	16.91	0.80	3.03
	Express	-1.6%	-0.2%	0.2%	0.0%	0.0%	-0.1%
	Arterial	-1.3%	-0.2%	0.1%	0.1%	0.1%	0.0%
Fuel (L/km)	None	0.128	0.146	0.142	0.260	0.128	0.111
	Express	-1.0%	-0.1%	0.0%	-0.1%	-0.2%	-0.1%
	Arterial	-1.1%	-0.6%	0.1%	0.0%	0.1%	0.0%
HC (g/km)	None	0.032	0.035	0.043	0.068	0.032	0.030
	Express	-0.9%	-0.4%	0.0%	0.0%	-0.1%	0.0%
	Arterial	-2.1%	-0.4%	0.0%	0.0%	0.1%	0.0%
CO (g/km)	None	0.983	1.163	1.346	1.997	0.856	0.877
	Express	-1.2%	-0.6%	0.0%	0.0%	-0.1%	0.0%
	Arterial	-3.0%	-0.4%	-0.1%	0.0%	0.1%	0.0%
NOx (g/km)	None	0.101	0.104	0.139	0.225	0.100	0.097
	Express	-0.3%	0.1%	0.0%	0.0%	-0.1%	0.0%
	Arterial	-0.5%	-0.4%	0.0%	0.0%	0.1%	0.0%

* Underlined numbers represent statistically significant changes at the 95 percent level based on a t-test (analysis not possible for EB Traffic, WB Traffic and Cross-Street Traffic)

TABLE 3 Impacts of Alternative Traffic Signal Control on Traffic Flow Performance

Performance Measure	Signal Control Scenario	Impacts on Traffic Groups			
		EB Traffic	WB Traffic	Cross-Street Traffic	All Traffic
		AM Peak			
Travel Time (s/veh)	Fixed	694.0	725.7	41.7	147.5
	Adaptive Splits	1.1%	-1.5%	2.0%	-1.1%
	Adaptive Splits+Offsets	5.6%	-2.9%	2.4%	0.8%
Delays (s/veh)	Fixed	337.5	325.1	26.6	68.2
	Adaptive Splits	2.2%	-3.4%	3.2%	-2.4%
	Adaptive Splits+Offsets	11.6%	-6.4%	3.8%	1.6%
Stops (stops/veh)	Fixed	15.21	15.21	0.91	2.65
	Adaptive Splits	-1.6%	-1.4%	2.6%	-0.9%
	Adaptive Splits+Offsets	3.8%	-0.9%	2.7%	1.9%
Fuel (L/km)	Fixed	0.289	0.116	0.083	0.111
	Adaptive Splits	0.4%	-0.5%	-2.9%	-0.5%
	Adaptive Splits+Offsets	2.5%	-1.2%	-2.5%	0.4%
HC (g/km)	Fixed	0.079	0.031	0.021	0.030
	Adaptive Splits	0.3%	0.3%	-1.4%	0.0%
	Adaptive Splits+Offsets	0.5%	-0.2%	-1.2%	0.1%
CO (g/km)	Fixed	2.380	0.920	0.539	0.880
	Adaptive Splits	0.2%	0.5%	-1.2%	0.1%
	Adaptive Splits+Offsets	0.0%	-0.1%	-1.0%	-0.1%
NOx (g/km)	Fixed	0.244	0.102	0.068	0.097
	Adaptive Splits	0.3%	0.1%	-0.8%	0.0%
	Adaptive Splits+Offsets	0.3%	0.0%	-0.7%	0.0%
		Midday			
Travel Time (s/veh)	Fixed	626.5	693.0	31.9	123.3
	Adaptive Splits	-2.6%	-2.0%	4.3%	-1.4%
	Adaptive Splits+Offsets	-0.3%	0.4%	4.4%	0.8%
Delays (s/veh)	Fixed	285.9	326.4	16.8	50.10
	Adaptive Splits	-5.6%	-4.2%	8.2%	-3.5%
	Adaptive Splits+Offsets	-0.6%	0.8%	8.4%	1.7%
Stops (stops/veh)	Fixed	14.71	15.93	0.86	2.43
	Adaptive Splits	-1.7%	-2.9%	2.4%	-1.5%
	Adaptive Splits+Offsets	1.9%	-1.2%	2.4%	0.9%
Fuel (L/km)	Fixed	0.160	0.161	0.061	0.108
	Adaptive Splits	-1.4%	-0.3%	0.1%	-0.8%
	Adaptive Splits+Offsets	-0.1%	1.3%	0.1%	0.3%
HC (g/km)	Fixed	0.048	0.048	0.017	0.031
	Adaptive Splits	-0.2%	0.0%	0.0%	-0.1%
	Adaptive Splits+Offsets	-0.1%	0.3%	-0.1%	0.1%
CO (g/km)	Fixed	1.516	1.530	0.450	0.969
	Adaptive Splits	-0.2%	0.1%	-0.3%	-0.1%
	Adaptive Splits+Offsets	-0.4%	0.3%	-0.4%	-0.1%
NOx (g/km)	Fixed	0.141	0.144	0.056	0.099
	Adaptive Splits	0.0%	-0.1%	-0.2%	-0.1%
	Adaptive Splits+Offsets	0.1%	0.4%	-0.2%	0.1%
		PM Peak			
Travel Time (s/veh)	Fixed	719.2	813.1	31.5	168.2
	Adaptive Splits	-0.2%	-3.6%	0.1%	-2.0%
	Adaptive Splits+Offsets	-0.3%	-5.2%	2.6%	-0.6%
Delays (s/veh)	Fixed	164.5	425.5	16.2	77.8
	Adaptive Splits	-0.7%	-6.8%	0.2%	-4.4%
	Adaptive Splits+Offsets	-1.3%	-10.0%	5.0%	-1.3%
Stops (stops/veh)	Fixed	9.81	16.91	0.80	3.07
	Adaptive Splits	0.0%	-4.0%	1.6%	-2.1%
	Adaptive Splits+Offsets	-0.1%	-5.7%	3.6%	0.5%
Fuel (L/km)	Fixed	0.142	0.260	0.128	0.111
	Adaptive Splits	-0.9%	-1.0%	-1.4%	-1.2%
	Adaptive Splits+Offsets	-1.0%	-0.5%	1.4%	-0.4%
HC (g/km)	Fixed	0.043	0.068	0.032	0.030
	Adaptive Splits	-0.2%	0.0%	-0.5%	-0.3%
	Adaptive Splits+Offsets	0.0%	0.2%	0.6%	0.0%
CO (g/km)	Fixed	1.346	1.997	0.856	0.879
	Adaptive Splits	-0.5%	0.2%	-0.3%	-0.3%
	Adaptive Splits+Offsets	-0.3%	0.6%	0.0%	-0.1%
NOx (g/km)	Fixed	0.139	0.225	0.100	0.097
	Adaptive Splits	0.0%	0.1%	-0.3%	-0.1%
	Adaptive Splits+Offsets	-0.1%	0.5%	-0.3%	-0.1%

* Underlined numbers represent statistically significant changes at the 95 percent level based on a t-test (analysis not possible for EB Traffic, WB Traffic and Cross-Street Traffic)

TABLE 4 Impacts of Transit Signal Priority under Adaptive Signal Control Scenarios

Performance Measure	Priority Scenario	Impacts on Traffic Groups											
		Adaptive Splits Control						Adaptive Splits and Offsets Control					
		Express Buses	Columbia Buses	EB Traffic	WB Traffic	Cross-Street Traffic	All Traffic	Express Buses	Columbia Buses	EB Traffic	WB Traffic	Cross-Street Traffic	All Traffic
		AM Peak						AM Peak					
Travel Time (s/veh)	None	849.4	729.2	701.3	714.7	42.6	144.3	874.8	734.0	733.0	704.8	42.7	147.1
	Express	-1.5%	-0.1%	0.0%	0.2%	-0.3%	0.1%	-1.7%	0.6%	0.1%	0.3%	-0.2%	0.1%
	Arterial	-1.5%	-4.2%	2.3%	1.6%	0.4%	2.0%	0.3%	-3.8%	1.2%	1.3%	0.2%	1.3%
Delays (s/veh)	None	486.4	441.7	344.8	314.1	27.4	65.6	511.8	446.4	376.5	304.2	27.6	68.3
	Express	-2.6%	-0.2%	0.0%	0.4%	-0.4%	0.1%	-2.9%	1.0%	0.2%	0.7%	-0.3%	0.1%
	Arterial	-2.6%	-6.9%	4.7%	3.6%	0.6%	4.4%	0.5%	-6.2%	2.4%	2.9%	0.3%	2.7%
Stops (stops/veh)	None	21.59	18.86	14.96	14.99	0.93	2.59	21.86	19.07	15.79	15.07	0.93	2.66
	Express	-1.0%	0.0%	0.1%	-0.3%	-0.1%	0.1%	0.3%	0.0%	0.2%	0.0%	0.0%	0.1%
	Arterial	-1.5%	-1.0%	0.6%	0.1%	-0.3%	0.9%	0.7%	-1.9%	0.2%	-0.3%	-0.5%	0.7%
Fuel (L/km)	None	0.145	0.154	0.290	0.115	0.081	0.109	0.146	0.154	0.296	0.114	0.081	0.111
	Express	-1.0%	-0.1%	0.0%	0.3%	-0.1%	0.0%	-0.2%	0.1%	0.1%	0.1%	0.0%	0.1%
	Arterial	-1.2%	-1.5%	1.0%	0.6%	0.6%	0.7%	0.2%	-1.8%	0.6%	0.4%	0.4%	0.5%
HC (g/km)	None	0.037	0.037	0.079	0.031	0.021	0.030	0.036	0.036	0.080	0.031	0.021	0.030
	Express	-1.4%	-0.7%	0.0%	0.2%	0.0%	0.0%	0.5%	0.2%	0.1%	0.1%	0.0%	0.1%
	Arterial	-1.3%	-1.3%	0.1%	0.2%	0.3%	0.1%	0.4%	-2.1%	0.2%	0.0%	0.3%	0.2%
CO (g/km)	None	1.212	1.201	2.385	0.924	0.532	0.877	1.158	1.183	2.380	0.919	0.533	0.876
	Express	-1.5%	-0.9%	0.0%	0.2%	0.0%	0.0%	0.5%	0.2%	0.1%	0.2%	0.0%	0.1%
	Arterial	-1.6%	-1.0%	-0.2%	0.1%	0.3%	0.0%	0.2%	-2.3%	0.0%	-0.1%	0.2%	0.1%
NOx (g/km)	None	0.105	0.106	0.244	0.102	0.067	0.097	0.104	0.106	0.244	0.102	0.067	0.097
	Express	-0.9%	-0.1%	0.0%	0.2%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%
	Arterial	-0.6%	-0.5%	0.0%	0.2%	0.2%	0.1%	-0.2%	-0.9%	0.1%	0.1%	0.2%	0.1%
		Midday						Midday					
Travel Time (s/veh)	None		796.3	610.4	679.3	33.3	120.8		813.9	624.6	695.6	33.3	123.5
	Express		0.0%	0.2%	0.0%	-0.3%	0.0%		-0.4%	0.1%	0.5%	-0.3%	0.0%
	Arterial		-3.1%	-0.3%	-0.3%	0.1%	0.0%		-4.6%	-0.4%	0.3%	0.2%	0.0%
Delays (s/veh)	None		491.0	269.8	312.7	18.2	47.9		508.4	284.0	329.0	18.2	50.5
	Express		0.0%	0.3%	0.0%	-0.5%	0.0%		-0.6%	0.1%	1.1%	-0.5%	0.1%
	Arterial		-5.1%	-0.6%	-0.6%	0.2%	0.0%		-7.4%	-0.9%	0.6%	0.4%	0.1%
Stops (stops/veh)	None		21.18	14.46	15.47	0.88	2.37		21.28	14.98	15.73	0.88	2.43
	Express		0.0%	-0.1%	0.2%	-0.2%	0.0%		0.3%	-0.6%	0.8%	-0.3%	0.1%
	Arterial		-0.7%	0.0%	-0.4%	0.0%	0.0%		-1.4%	-0.6%	0.8%	0.2%	0.1%
Fuel (L/km)	None		0.157	0.157	0.160	0.061	0.106		0.158	0.160	0.163	0.061	0.108
	Express		0.0%	0.1%	-0.1%	-0.1%	0.0%		0.0%	-0.1%	0.2%	-0.1%	0.0%
	Arterial		-1.2%	0.0%	-0.1%	0.0%	0.0%		-1.6%	-0.1%	0.1%	0.1%	0.0%
HC (g/km)	None		0.041	0.048	0.048	0.017	0.031		0.040	0.048	0.049	0.017	0.031
	Express		0.1%	-0.1%	0.0%	0.0%	0.0%		0.1%	-0.1%	0.0%	0.1%	0.0%
	Arterial		-1.1%	0.0%	-0.1%	0.0%	0.0%		-0.3%	0.1%	-0.1%	0.1%	0.1%
CO (g/km)	None		1.411	1.514	1.532	0.448	0.966		1.362	1.511	1.535	0.448	0.966
	Express		-0.1%	-0.1%	0.0%	0.0%	0.0%		0.3%	-0.2%	-0.1%	0.2%	0.0%
	Arterial		-1.3%	0.0%	0.0%	0.0%	0.1%		0.1%	0.2%	0.0%	0.2%	0.1%
NOx (g/km)	None		0.109	0.141	0.144	0.056	0.098		0.109	0.141	0.145	0.056	0.099
	Express		-0.1%	0.0%	-0.1%	0.0%	0.0%		-0.2%	-0.1%	0.0%	0.0%	0.0%
	Arterial		-0.7%	0.0%	-0.1%	0.0%	0.0%		-0.4%	0.0%	-0.1%	0.0%	0.0%
		PM Peak						PM Peak					
Travel Time (s/veh)	None	737.2	605.8	718.1	784.0	31.6	163.7	786.1	620.3	717.1	770.6	32.3	166.1
	Express	-0.9%	0.3%	-0.1%	-0.1%	-0.4%	-0.2%	-3.0%	-0.2%	0.1%	-0.1%	0.1%	-0.1%
	Arterial	-0.5%	-1.6%	0.1%	0.5%	0.1%	0.2%	-1.7%	-2.6%	0.1%	0.4%	0.9%	0.4%
Delays (s/veh)	None	350.7	337.0	163.4	396.4	16.3	73.7	399.7	351.6	162.4	383.0	17.0	76.1
	Express	-2.0%	0.5%	-0.4%	-0.2%	-0.7%	-0.4%	-5.9%	-0.4%	0.3%	-0.3%	0.2%	0.0%
	Arterial	-1.1%	-3.0%	0.5%	1.1%	0.2%	0.6%	-3.4%	-4.6%	0.6%	0.8%	1.8%	0.9%
Stops (stops/veh)	None	18.09	16.67	9.81	16.24	0.81	2.97	19.51	17.03	9.79	15.96	0.83	3.04
	Express	-0.1%	-0.4%	0.2%	0.2%	-0.2%	0.0%	-1.0%	-0.4%	-0.3%	0.5%	-0.4%	-0.1%
	Arterial	-0.2%	-0.6%	-0.2%	0.4%	0.0%	0.1%	-0.3%	-0.7%	-0.4%	0.2%	0.1%	0.1%
Fuel (L/km)	None	0.126	0.145	0.141	0.258	0.126	0.110	0.130	0.147	0.141	0.259	0.130	0.111
	Express	-0.3%	-0.2%	0.0%	-0.1%	-0.2%	0.0%	-1.0%	-0.4%	-0.1%	0.0%	-0.2%	0.0%
	Arterial	-0.3%	-0.9%	0.1%	0.1%	0.0%	0.1%	-0.4%	-1.0%	0.0%	0.1%	0.2%	0.1%
HC (g/km)	None	0.032	0.035	0.043	0.068	0.032	0.030	0.032	0.035	0.043	0.068	0.032	0.030
	Express	0.4%	-1.1%	0.0%	-0.1%	-0.1%	0.0%	0.3%	-0.6%	-0.2%	-0.1%	-0.1%	0.0%
	Arterial	-0.7%	-1.0%	0.0%	0.0%	-0.1%	0.1%	1.5%	-0.4%	-0.1%	0.1%	0.2%	0.1%
CO (g/km)	None	0.989	1.155	1.339	2.001	0.854	0.874	0.965	1.158	1.342	2.009	0.856	0.876
	Express	0.4%	-1.5%	0.0%	-0.1%	-0.1%	0.0%	0.8%	-1.0%	-0.2%	-0.1%	-0.2%	-0.1%
	Arterial	-0.8%	-1.2%	0.0%	-0.1%	-0.1%	0.0%	2.4%	-0.4%	-0.2%	0.1%	0.1%	0.0%
NOx (g/km)	None	0.101	0.104	0.139	0.225	0.100	0.097	0.100	0.104	0.139	0.226	0.100	0.097
	Express	0.1%	-0.3%	0.0%	-0.1%	-0.1%	0.0%	-0.1%	-0.4%	-0.1%	-0.1%	-0.1%	0.0%
	Arterial	0.1%	-0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	-0.5%	-0.1%	0.0%	0.1%	0.0%

* Underlined numbers represent statistically significant changes at the 95 percent level based on a t-test (analysis not possible for EB Traffic, WB Traffic and Cross-Street Traffic)

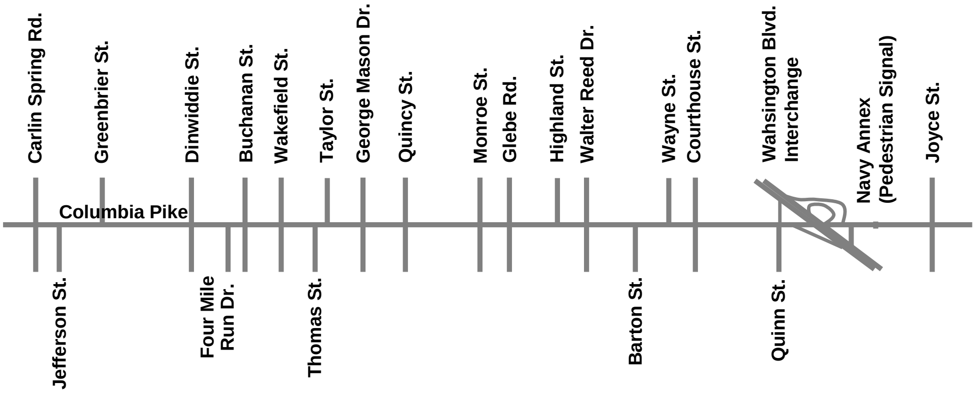

FIGURE 1 Study corridor.

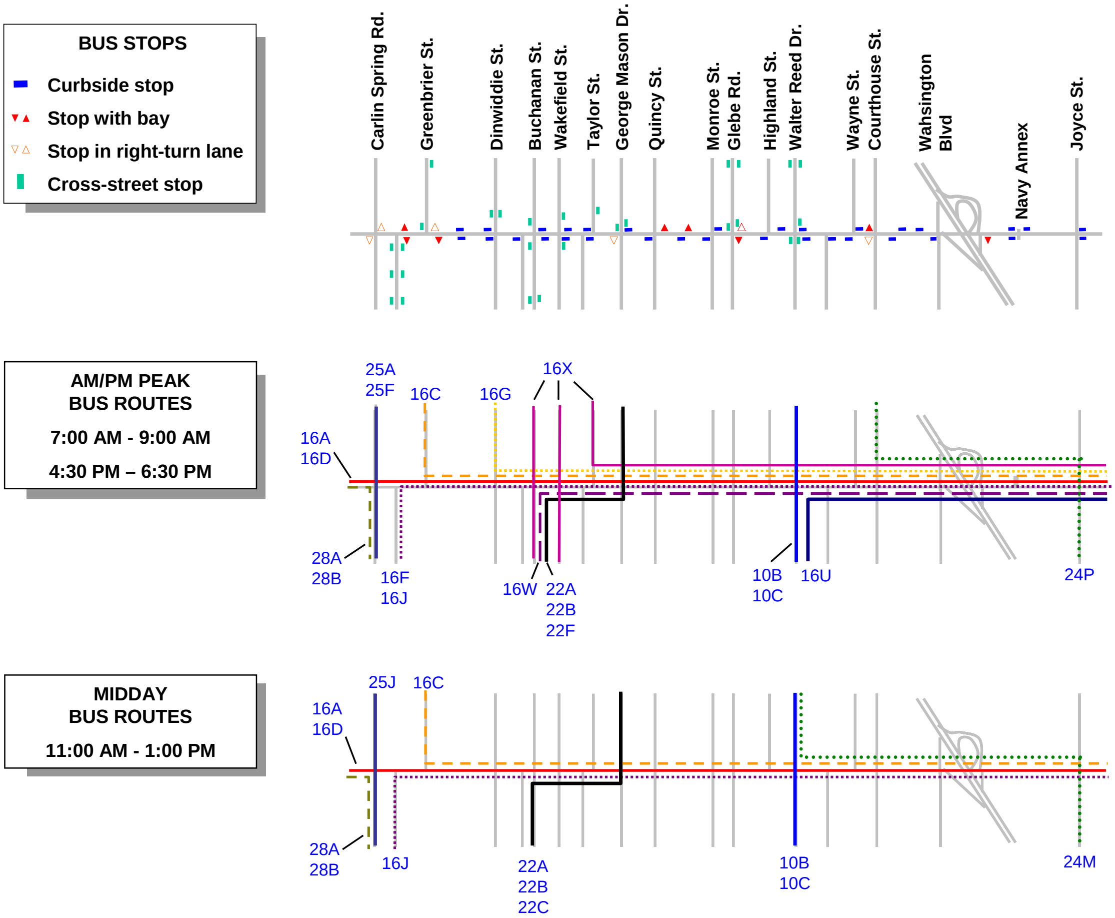

FIGURE 2 Transit service along study corridor.