EVALUATION OF POTENTIAL TRANSIT SIGNAL PRIORITY BENEFITS ALONG A FIXED-TIME SIGNALIZED ARTERIAL

By

François Dion
Research Scientist
Virginia Tech Transportation Institute
3500 Transportation Research Plaza (0536)
Blacksburg. VA 24061

Phone: (540) 231-1507
Fax: (540) 231-1555
E-mail: fdion@vtti.vt.edu

Hesham Rakha
(Corresponding Author)
Associate Professor, Charles Via Department of Civil and Environmental Engineering
Leader, Transportation Systems and Operations Group
Virginia Tech Transportation Institute
3500 Transportation Research Plaza (0536)
Blacksburg. VA 24061

Phone: (540) 231-1505
Fax: (540) 231-1555
E-mail: rakha@vtti.vt.edu

and

Yihua Zhang
Graduate Student
Virginia Tech Transportation Institute
3500 Transportation Research Plaza
Blacksburg. VA 24061

ABSTRACT

This paper presents the findings of a study evaluating the potential benefits of implementing transit signal priority along the Columbia Pike arterial corridor, in Arlington, Virginia. The study uses the INTEGRATION microscopic traffic simulation model to evaluate the impact of a number of alternative priority strategies on both the prioritized buses and general traffic during the AM peak and Midday traffic periods. The transit priority strategies considered include providing priority to express buses traveling along Columbia Pike, to both express and regular buses along the arterial, and to all buses within the study corridor. The priority logic that is considered in the study provides simple green extensions and green recalls within a fixed-time traffic signal control environment. The simulation results indicate that the buses provided with priority would typically benefit from transit priority, but that these benefits may be obtained at the expense of the overall traffic, particularly when traffic demand is high. However, it is also found that in periods of lesser demand, the overall negative impacts could be negligible due to the availability of spare capacity at the signalized intersections.

INTRODUCTION

While many factors influence urban transit services, delays induced by the operation of traffic signals typically accounts for 10 to 25% of the total travel time of buses (Sunkari et al., 1995). To minimize these delays, preferential treatment can be granted to buses at signalized intersections, either off-line, by determining signal timings that intentionally favor bus movements, or on-line, by allowing the signal timings to adjust to bus is detections. In the latter case, the signal timings are typically allowed to hold the green on an approach until the bus has cleared the intersection, or to advance the start of the green to reduce the delay incurred by a bus in queue. Other options may also include the implementation of bus-activated exclusive phases and the skipping of non-transit service phases.

While the use of signal priority has been widely accepted at isolated intersections, there has been significant resistance in its use within coordinated signalized systems due to potential adverse impacts on general traffic. In particular, it has been argued that phase skipping and red truncation could confuse motorists, impact signal coordination, and cause significant delays to the general traffic, particularly on streets crossing the transit routes. Another problem is linked with the inherent variability of transit dwell times, which introduces uncertainty in the predictions of vehicle arrivals. Despite these negative elements, Garrow and Machemehl (1997) indicates that priority strategies may be successfully implemented along urban arterials. In their extensive literature review, they indicates that transit priority can offer significant potential benefits to buses without seriously compromising competing traffic if the priority system is developed with the needs of the entire transportation network in mind. However, they also indicate that the success of transit priority systems greatly depends on the specific characteristics of each network.

This paper describes a simulation study that evaluates the potential benefits of implementing transit priority along an urban arterial in the Washington D.C. region. The objective of the paper is two-fold. First, it is to present results that are specific for the Columbia Pike corridor, and second, to attempts to generalize the results of the study to identify conditions under which transit signal priority might be detrimental to the overall system performance. The paper starts with a brief review of previous transit priority evaluations and then successively presents the main characteristics of the selected study corridor, the simulation model that was developed, the transit priority logic considered, the evaluation scenarios considered, and the main results and conclusions of the study.

LITTERATURE REVIEW

Transit priority at signalized intersections has been studied in the United States since the 1970s (Evans and Skiles, 1970). While numerous studies have been reported over the years (Chang and Vasudevan, 1995; Baker *et al.*, 2002), only a few of these describe field trials and implementation results. Due to the high cost of conducting field evaluations, the majority of the reported studies describe results from simulation evaluations.

The various studies that were performed generally indicate that buses may benefit from priority systems. For example, in a recent review of field trial and implementation evaluations, Baker *et al*. (2002) indicate that various priority systems that were tested produced reductions in transit signal delay for prioritized buses at individual intersections ranging between 6 and 57%, and reductions in overall bus travel times between 0 to 8%. Vehicles traveling on the same approaches as the buses receiving priority also often experienced reduced delays as a result of the increase in green time to accommodate buses. Other potential benefits from transit priority include improved transit schedule reliability, increased rider comfort, reduced vehicle fuel consumption and emissions, reduced wear and tear on equipment, and ultimately, increased attractiveness of the transit mode of travel.

Potential adverse effects of transit priority generally include increased delays and queue lengths for vehicles traveling on cross-streets. Disruption of traffic patterns along coordinated arterials can also result in increased vehicle stops and delays along prioritized corridors (Al-Sahili and Taylor, 1996). As a result of these impacts, there is no a priori insurance that transit priority will yield overall benefits at a corridor level. This supports the earlier statement indicating that the success of transit priority depends greatly on the characteristics of each transportation network.

STUDY CORRIDOR

For the study presented in this paper, the Columbia Pike arterial that runs through Arlington County in the Northern Virginia section of the Washington D.C. metropolitan area was selected as a test corridor. This arterial is the main county east-west traffic corridor and carries on average approximately 26,000 vehicles per day. In addition to serving large federal agencies such as the Pentagon and Navy Annex at its eastern end, it links residential and medium-density retail business neighborhoods. In term of transit operations, the arterial exhibits the highest ridership of any bus corridor in Virginia, with over 9,000 transit daily trips made along the corridor.

Geometric Considerations

Figure 1 illustrates the geometry of the corridor. The corridor extends over 6.35 kilometers (3.95 miles) and covers 20 signalized intersections and one freeway-type interchange. Of these 21 intersections, the Carlin Spring, George Mason, Glebe, Walter Reed, Washington Blvd, and Joyce intersections carry significant cross-street traffic. A traffic signal is also located in front of the Navy Annex building to allow pedestrians to access the bus stop located immediately across the street.

In terms of horizontal alignment, the corridor features a relatively straight alignment. The only major curve, not shown in Figure 1, is between the Navy Annex pedestrian signal and the intersection with Joyce, where the arterial makes a 90-degree turn. In terms of vertical alignment, the corridor presents a number of significant uphill and downhill sections. These grades must be considered as they affect the acceleration and deceleration behavior of vehicles, particularly of buses carrying large number of passengers. The steepest grades are found between the signals at the Navy Annex and Joyce (6.5%), Taylor and Quincy (4.3%), and Wakefield and Thomas (4.0%).

Traffic Conditions

Traffic flow along the corridor is highly directional. During the AM peak period (6:00 – 9:00 AM), traffic along Columbia Pike generally moves eastward, towards the Pentagon and downtown Washington D.C., while traffic on the cross streets generally travel northbound. During the afternoon peak (3:30 - 7:00 PM), motorists returning home create opposite trends. During the remainder of the day traffic between demands are generally more balanced across the various signalized approaches.

For illustrative purposes, Figure 2 displays the 15-minute average flows that were recorded by the traffic detectors installed on the eastbound and westbound approach to the intersection with George Mason. The figure clearly indicates the directionality of traffic movements during peak periods, as well as the variability of traffic from one day to the next. In this case, a day-to-day comparison of the flow data indicates that traffic volumes for individual 15-minute periods often vary by as much as 20% from one day to the next. This is again important, as flow variations are likely to create uncertainty in the potential benefits that can be achieved with transit priority.

Signal Operations

Traffic movements between Dinwiddie and Courthouse are normally controlled by a SCOOT (Splits Cycle Offset Optimization Tool) real-time traffic signal control system (Hunt *et al.*, 1981) while other intersections are controlled using traditional time-of-day fixed-time control. For this study, however, fixed-time operation is assumed for the entire corridor. First, to reflect the fact that transit priority systems are typically implemented within fixed-time control. Second, to allow the impacts of transit signal priority to be evaluated without the impacts of other confounding factors such as adaptive traffic signal control. This assumption may result in larger benefits to buses with potential larger negative impacts on general traffic since the traffic control system will then not be able to adjust the timings of individual intersections to observed changes in traffic conditions caused by the granting of priority requests.

For all intersections, existing fixed-time signal timing plans for non-SCOOT intersections and default background fixed-time plans for SCOOT intersections were obtained from the Department of Public Works of Arlington County. The SCOOT background timing plans were in general very close to the average signal timings implemented by the SCOOT system. Since these timing plans were developed less than a year before the study, they were considered to be representative of optimal fixed-time control. This implies that few benefits, if any, should be indirectly derived from the correction of a non-optimal traffic signal control situation.

Transit Operations

Figure 3 illustrates the bus routes serving the corridor and the location of bus stops. For simplicity it is assumed that buses service all transit stops along their route. This assumption is close to current transit operations along the corridor. 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. For instance, stops requiring buses to dwell on traffic lanes create temporary bottlenecks that may reduce the flow of vehicles going through intersections. The figure further categorizes bus stops according to their relative position with respect to the signalized intersections. In this case, the mix of far-side, near-side and mid-block stops adds to the complexity of the evaluation, as different stop locations do not require the same changes in signal timings to accommodate buses. For instance, dwell times must be accounted for when considering near-side stops, but not with far-side stops. Finally, the figure indicates a number of intersections where priority conflicts could arise between Columbia Pike and cross-street buses.

SIMULATION MODEL SETUP

The INTEGRATION microscopic traffic simulation model (M. Van Aerde and Associates, 2002; Rakha and Ahn, In press) is used to evaluate the potential benefits of providing transit priority along Columbia Pike. This model has been in continuous development over the past 15 years and has been the subject of numerous validations. It was conceived as an integrated simulation and traffic assignment model and performs traffic simulations by tracking the movement of individual vehicles every 1/10th of a second. This allows detailed analyses of lane changing movements and shock wave propagations. It also permits considerable flexibility in representing spatial and temporal variations in traffic conditions. In addition to estimating stops and delay (Rakha *et al.*, 2001; Dion *et al.*, In press), the model can also estimate the fuel consumed by individual vehicles, as well as the emissions of hydrocarbon (HC), carbon monoxide (CO) and oxides of nitrogen (NO_x). 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 level (Rakha and Ahn, In press; Ahn *et al.*, 2002).

Within the simulation model, 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 this modeling was derived from field data, except for the saturation flows, which were assumed to be 1900 vehicles per hour of green per lane in the absence of actual field observations. This value corresponds to the ideal saturation flow in the 2000 Highway Capacity Manual (TRB, 2000) and was chosen given the high geometric design of the arterial considered in the study. Furthermore, while speed limits of 48 and 56 km/h (30 and 35 mph) are posted along the corridor, GPS measurements indicated that typical travel speeds oscillate between 65 and 70 km/h (40 and 45 mph). Thus, in order to reflect field conditions, measured free-flow speeds were utilized.

To account for the temporal variations in traffic flows, the traffic demand was modeled using 15-minute intervals. For each interval, the demand was expressed in the form of a fixed origin-destination matrix. This matrix was calibrated using the QueensOD model (Van Aerde *et al.*, 2003; M. Van Aerde and Associates, 1998), which was developed to support the INTEGRATION model. The calibration produced maximum likelihood synthetic O-D demand matrices that minimizes the relative error between observed and synthetically generated link flows. These matrices were generated based on traffic flow data from loop traffic detectors installed on most intersection approaches within the SCOOT-controlled section of the corridor, and on additional manual vehicle counts that were conducted at key major intersections to estimate turning movements. Such information could not be derived from the loop detector data since the SCOOT system requires its detectors to be placed as far upstream as possible from the controlled intersection, typically just downstream of the upstream intersection, and thus upstream of the point where traffic splits into through and turning movements.

Traffic demand calibrations were made for individual 15-minute periods. Figure 4 illustrates the result of the calibration that was conducted for the 8:00 – 8:15 AM interval. Similar graphs were obtained for the other time intervals. The figure indicates a very good agreement between simulated and observed flows for all links with average hourly flow below 1300 veh/h while significant discrepancies are observed for links with flows above 1300 veh/h. As can be observed, these discrepancies are all associated with links with data from manual counts. These discrepancies can first be attributed to differences between the SCOOT detector data and the manual traffic counts, as the two data sets reflect traffic conditions one week apart. Since the calibration model was instructed to minimize the relative error between the observed and simulated flows, it was also expected that larger discrepancies would occur for links with high volumes. In addition, since there were more links with loop detector data than manual counts, the calibration thus produced synthetic link flows that generally matched the detector data from the SCOOT system. In general, however, a visual analysis of simulation runs indicated a reasonable match between the simulated and observed traffic conditions along the corridor, particularly in the location of congested areas and length of resulting traffic queues.

Transit operations were 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-second average service time and a 10% 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. This has an important consequence on traffic signal operations, as buses arriving at different periods within a cycle may require the implementation of different transit priority options.

TRANSIT PRIORITY LOGIC

The transit priority logic in version 2.30f of the INTEGRATION model attempts to replicate the actions of state-of-practice signal priority systems considering only green signal extensions and early green recalls. The main elements of this logic are summarized below:

- Approaching buses are detected at a user-specified distance upstream of the signal stop line. In this case, the distance was set at 100 meters (328 feet).
- If a bus is projected to enter the intersection during the green interval, no alteration is made to the signal timings.
- If a bus is projected to arrive after the end of the green, the interval is extended at increments of *n* seconds until either the vehicle has left the approach or the maximum allowable green duration is reached. The green time required for the extensions is taken from the next phase in the cycle that has not been reduced to its minimum allowed duration.
- If a bus is detected while traffic on another approach is being served, the active green phase is terminated after an increment of *n* seconds, or as soon as the defined minimum green time requirement for that phase is satisfied, to allow the green signal to be returned to the approach with the bus as quickly as possible. The green signal is returned to the prioritized approach only after having satisfied both the specified minimum green and intergreen (amber plus all-red) intervals of all the intermediate phases that are defined in the phase sequence. Following the early green recall, the green time on the prioritized approach is then terminated at its normal end point.
- If a priority request had 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.
- If two or more requests are simultaneously received from conflicting approaches, no changes are made to the signal timings given that there is no means to prioritize the priority requests.

This logic is further subject to the four following constraints:

- Service of the minimum green time assigned to each phase by the user.
- Green extensions cannot result in green phases exceeding their maximum defined duration.
- No changes allowed to the cycle length, to preserve coordination with adjacent intersections.
- No phase skipping is allowed 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 green phase subject to a green extension request. This equation defines the maximum green as the time that remains within a signal cycle after subtracting all intergreen intervals and the specified minimum greens of all conflicting green phases within the cycle.

$$ge_{\max i} = min\left(g_{max\,i}\ ;\ C - a_i - \sum_{j=1}^{n}\left(g_{min\,j} + a_j\right)\ for\ all\ j \neq i \right) \qquad [1]$$

where: $ge_{max\,i}$ = Maximum green duration of phase *i* when granting extensions,
$g_{max\,i}$ = User-defined maximum green duration of phase *i*,
$g_{min\,j}$ = User-defined minimum green duration of phase *j*,
C = Signal cycle length,
a_j = Intergreen (amber + all red) interval duration at end of phase *j*, and
n = Number of phases defined within signal cycle.

While the INTEGRATION model does not explicitly consider pedestrians, minimum pedestrian crossing times can easily be taken into consideration 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. However, no means are currently provided for modeling pedestrian clearance intervals. Since such intervals are typically implemented as a first termination stage of a green phase and are usually fixed in nature, they can be viewed as being part of the intergreen intervals.

The assumption that the reception of simultaneous conflicting priority requests result in no priority addresses the difficulties of handling such cases and the numerous potential solutions that can resolve such conflicts. Most of these solutions require information that is not currently typically available to traffic signal controllers. For instance, priority could be given to the vehicle having the highest occupancy. However, this requires knowledge of transit ridership near each intersection along each transit route. Priority could also be given to the vehicle that is farthest behind schedule. This requires the capability of detecting vehicle actual arrivals times at transit stops. Priority could further be based on the level of congestion observed on each approach. Modifications to the INTEGRATION transit priority logic are underway to consider a number of the above mentioned options.

EVALUATION SCENARIOS

To evaluate the potential benefits of providing transit priority along Columbia Pike, four priority scenarios were developed:

- **Base Scenario**: No priority.
- **Scenario 1**: Priority to express buses traveling along Columbia Pike between Dinwiddie and Quinn (Route 16J).
- **Scenario 2**: Priority to regular and express buses traveling along Columbia Pike between Dinwiddie and Quinn (Routes 16 and 24).
- **Scenario 3**: Priority to all buses traveling between Dinwiddie and Quinn

In each case, a default green extension interval of 5 seconds was used. A 5-second minimum green time duration for all phases was also used. Such a short minimum green time was set to determine the maximum benefits that could be obtained from the various priority strategies considered. An analysis of the impacts of using longer or shorter green extension intervals was also conducted and provided in the evaluation section.

Two evaluation periods were further selected. The first simulates observed traffic during the AM peak period between 7:00 AM and 9:00 AM, while the second simulates observed midday traffic between 11:00 AM and 1:00 PM. The first period allows evaluations with relatively high and directional traffic flows, while the second allows evaluations with less traffic demand and more balanced flows. Evaluations during the PM peak period were not considered.

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

For each scenario, 30 two-hour simulation runs were conducted to account for the stochastic nature of the traffic simulation. Within each run, performance measures compiled on person travel time, person delay, vehicle stops, vehicle fuel consumption, and vehicle emissions of HC, CO and NO_x. Person-based travel time and delay statistics were compiled instead of vehicle-based measures 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. Finally, vehicle emissions are considered to assess the potential environmental impacts of the various strategies considered. While these impacts might not be of prime interest to transit agencies, they are important for environmental conformance analyses.

In all cases, simulations were done while considering only vehicles traveling along Columbia Pike. The examination of whether motorist will change their route as a result of the implementation of transit priority was not considered even though the INTEGRATION model has the capability of performing dynamic traffic assignments. This decision is based on the fact that motorists who do not intend to access the residential roads along the modeled section of Columbia are already more likely to use Arlington Boulevard to the north or the I-395 to the south for longer distance travel. In addition, as will demonstrated in the next section, most of the scenarios did not change vehicle performance measures to such an extent as to create any significant change in travel behavior.

SIMULATION RESULTS

For the AM peak, the initial simulation results indicated that the provision of transit priority at all intersections between Dinwiddie and Queen was generally beneficial to buses. For the Columbia Pike express buses, statistically significant reductions in travel time (-2.3 to -2.5%), delays (-3.7 to -4.1%), vehicle stops (-1.3 to -2.7%), and fuel consumption (-1.1 to -2.7%) were obtained when priority was provided exclusively to them or in conjunction with other buses running along the arterial. Regular Columbia Pike buses also experienced statistically significant reductions in travel time (-4.8%), delay (-7.6%), stops (-1.8%), and fuel consumption (-1.9%) when priority was granted to them.

For the general traffic, however, the priority strategies generally caused negative impacts. Increases in person travel time and delays were particularly important for the strategies considering all buses running along Columbia Pike and all buses within the corridor. For these two scenarios, transit priority resulted in over 18% increases in average travel time and 14% increases in average delay for the general traffic. Much less negative impacts were obtained when priority was granted exclusively to express buses since there are only 10 of such buses in comparison to 61 regular buses.

To identify the causes of such significant increases in travel time and delay, an analysis of intersection specific delays was considered. This analysis revealed that the travel time and delay increases were mostly attributed to delay increases incurred by vehicles traveling on the northbound and southbound approaches to the intersections with George Mason and Walter Reed. Observed increases in average delay varied between 45 and 160 seconds per vehicle. On the approaches to other intersections, the implementation of transit priority resulted in average delay increases of no more than 19 s/veh. For most of the approaches, the increases remained less than 10 s/veh, with some approaches even exhibiting reductions in average travel time up to 3 s/veh.

The large delay increases that were observed at the intersections with George Mason and Walter Reed were attributed to the fact that these two intersections carry significant cross-street traffic. In both cases, the disruption of signal timings to accommodate buses along Columbia Pike resulted in a reduction of average green time being provided to the cross-streets. Since there are large traffic volumes on these cross-streets, and thus very little spare green time under normal conditions, any reduction in green time on these cross-street approaches is thus sufficient to create congestion on them. This situation also exists when priority is provided to cross-street buses since there are more priority calls coming from buses running along Columbia Pike than from buses running on George Mason or Walter Reed.

Consequently, a new set of simulations was conducted for the AM peak scenarios in which transit priority was not provided at the intersections with George Mason and Walter Reed. This change marginally reduced the benefits to buses but significantly reduced the negative network-wide impacts of transit priority. In this case, maximum increases in travel time, delays, stop and fuel consumption incurred by the general traffic were reduced from 19.3 to 5.7%, 26.4 to 8.7%, and 4.7 to 1.8%, and 4.8 to 2.4%, respectively. Tables 2 and 3 detail the performance measures that were compiled for the various priority scenarios considered. Table 4 further lists the relative changes in each performance measure and indicates whether the observed changes are statistically significant based on a paired student t-test with a 95-percent confidence level.

Under the revised strategy, benefits for the 10 express buses are now virtually non-existent, with reductions in travel time and delays of less than 0.3% and some increases in vehicle stops and fuel consumption. Columbia Pike buses still experience statistically significant reductions in travel time (2.6%), delays (4.3%), stops (1.0%), and fuel consumption (1.1%) during the AM peak period when priority is exclusively granted to them. For the cross-street buses, the potential benefits include significant reductions in travel time (3.5%), delays (6.4%), stops (0.9%) and fuel consumption (1.3%) when they are provided with priority with the arterial buses. In this case, the larger reductions in performance measures for cross-street buses are a consequence of the shorter green time that are normally given to the cross streets. Because of these shorter green times, cross-street buses tend to wait longer at red signals. Thus, any transfer of green time from Columbia Pike to the cross-streets has a greater potential for improving transit operations.

For the Midday period, buses again generally benefit from the various priority strategies. For the buses running along Columbia Pike, Table 4 indicates significant reductions in travel time (3.1-3.2%), delays (4.9-5.1%), vehicle stops (0.6%), and fuel consumption (1.0-1.1%) when priority is granted at all intersections, including George Mason and Walter Reed. In this case, the ability to obtain benefits while providing priority at all intersections is attributed to the lower midday traffic demand, which provides for more spare capacity and thus, for an increased ability to re-allocate the green time without causing temporary over-saturation on some intersection approaches. The fact that there are less buses running along the corridor also plays another important role since there are less instances in which traffic signal timings are modified. For the cross-street buses, significant reductions in travel time (10.5%), delays (17.0%), stops (4.2%) and fuel consumption (3.0%) also result from the provision of transit priority to these vehicles.

In terms of overall benefits, none of the priority strategies yielded system-wide reductions in performance measures. However, none of the strategies also resulted in significant increases in these measures. This is particularly true for the scenario providing priority to buses along Columbia Pike. In this case, reductions in travel time, delay, stops and fuel consumption are observed without excessive costs to the general traffic. As shown in Table 4, this scenario did not increase system-wide travel time during the AM peak period by more than 1.2%, delays by more than 2.7%, stops by more than 0.9%, and fuel consumption by 1.1%. Assuming a higher bus ridership of 50 passengers per vehicle, further reductions in system-wide negative impacts are observed. Travel time is now only increased by 0.7%, delay by 1.5%, and stops by 0.4%. For the Midday period, small reductions of up to 0.4% in system-wide performance measures are observed with the assumed 16-person vehicle occupancy. In this case, a 50-person bus occupancy rate would further result in overall travel time reduction of 0.8%, delay reduction of 1.6% and stop reduction of 0.4%. These results indicate that for off-peak periods, transit priority could be successfully implemented along the corridor under any occupancy rate without causing any significant deterioration in general traffic operations. For the AM peak period, transit priority could be provided to buses running along Columbia Pike only when transit occupancies are high enough and when any resulting negative impacts on general traffic are deemed reasonable. The study also demonstrates that transit priority should not be granted at intersections with opposing approaches with significant congestion (typically with volume-to-capacity ratio above 80%).

One initial assumption that was invalided by the study is that vehicles traveling along Columbia Pike would automatically benefit from transit priority. While some vehicles were indeed observed to benefit from an early green recall or a green extension awarded to a bus at some intersections, these same vehicles were also observed to often wait longer at subsequent intersections. One reason for these longer wait times is that buses, contrary to cars, have to stop at service points between intersections. Thus, while a platoon of vehicles may benefit from an early green recall at one intersection, vehicles within this platoon would typically reach the next intersection before the arrival of the bus and may therefore have to wait for the normally scheduled green before being able to continue their trip. In another example, vehicles following a bus receiving an early green recall at a signalized intersection may not be able to follow the bus across the next intersection if priority takes the form of a green extension.

In terms of environmental impacts, the simulation results do not provide conclusive trends. Depending on the scenario considered, either increases or reductions in emissions of HC, CO and NO_x are observed. In most cases, the changes are less than 1% and not significant. These results can be explained by the fact that vehicle emissions are not only dependent on the number of vehicle stops made and the total travel time, but also on the behavior of individual drivers, and particularly on the variability of travel speeds. Thus, while a given scenario may yield overall reductions in travel time and stops, changes in the underlying travel behavior may lead to either decreases or increases in vehicle emissions.

A final evaluation looked at the impact of the length of the green extension interval on system performance. As previously indicated, a 5-second green extension increment was initially used. To determine the impacts of using different increments, 30 simulation runs were conducted for scenarios considering 2, 3, 4, 6 and 10-second green extensions. Table 5 indicates the relative impacts of each assumed extension on transit and general traffic performance for both the AM and Midday period when providing priority to Columbia Pike buses only. For both periods, it is observed that the duration of the green extension has little impact on the performance of buses receiving priority. These results were expected since the priority system explicitly attempts to provide the number of extensions required to accommodate buses. A change in the green extension interval duration thus mainly results in a change in the number of extensions requested until a bus is served. However, in terms of general traffic operations, it is observed in both periods that longer green extensions tend to reduce overall travel time, delay, stops, fuel consumption and emissions. This is explained by the fact that the use of longer extensions tend to increase the amount of green time provided along Columbia Pike, often beyond what is strictly required to let a bus pass, thus increasing the green time allocated to the high demand signalized approaches.

CONCLUSIONS

The main conclusions that can be drawn from the study is that transit priority could be provided to buses running along Columbia Pike in both the AM peak and Midday period without significantly impacting the general traffic. In both cases, the simulation results indicate that buses experience reduced travel time, delay, stops and fuel consumption as a result of transit signal priority. However, no conclusive impacts on vehicle emissions are observed. Network-wide negative impacts of transit priority can be minimized by only providing priority at signalized intersections where conflicting approaches are operating below capacity (volume-to-capacity ratio less than 80%). During periods of low demand, transit priority results in minimum network-wide disbenefits because of the lower congestion on the conflicting signalized approaches and the lower number of buses requesting priority.

While the results of the study are specific to the Columbia Pike arterial, they are in line with previous studies indicating that buses generally benefit from transit priority while there is no a priori guarantee that priority yields overall system-wide benefits when the general traffic is also taken into consideration. The study has demonstrated that the benefits of transit priority along a signalized corridor are particularly dependent on the level of transit ridership, level of arterial and cross-street traffic, the level of optimality of the traffic signal plan in operation, and the location of the bus stops relative to a signalized intersection. The simulation results clearly demonstrate that higher transit ridership increases the potential benefits of transit priority while higher cross-street traffic increases the risk of negative impacts. When applied on an arterial with timings plans that are sub-optimal, transit priority could also indirectly help improve traffic operations if it results in increased green time being allocated on intersection approaches with less than optimal green times. The location of bus stops, finally, dictates whether early green recalls or green extensions are required. A more detailed analysis of the sensitivity of transit priority impacts to various traffic signal timing and bus location parameters is beyond the scope of this paper but described in detail in the literature (Rakha and Zhang, 2003).

Of particular interest in this case would be to evaluate the benefits that could be obtained from providing priority to buses along Columbia Pike while traffic is controlled with the existing traffic-adaptive SCOOT system. Another refinement would be to look at various conditional priority strategies. Two potential criteria would be to deny priority to buses that have less than a certain number of passengers aboard or to buses that are running ahead of their schedule. The level of traffic flow with respect to capacity at individual intersections could also be used to determine whether providing priority to an approaching bus is warranted given the potential negative impacts of providing such priority. All these conditional elements carry with them the potential of providing priority to buses with reduced impacts on general traffic performance.

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TABLE 1 Simulation Summary Statistics

Measure	Simulated Vehicles	Traveled Distance (km)	Occupancy (pers/veh)
AM Peak Period			
Express Buses	10	71	23
Regular Buses	61	333	23
Cross-Street Buses	43	39	23
Cars	27600	40,683	1.2
All Vehicles	27714	41,126	N/A
Midday Period			
Express Buses	0	0	16
Regular Buses	22	135	16
Cross-Street Buses	30	28	16
Cars	21,437	30,350	1.2
All Vehicles	21,490	30.513	N/A

TABLE 2 Simulated Performance Measures for AM Scenarios with 5-second green extension interval

Measure	Buses Wth Priority	Express Buses		Regular Buses		Cross-Street Buses		Cars		All Traffic	
		Mean	Variance	Mean	Variance	Mean	Variance	Mean	Variance	Mean	Variance
Travel Time (sec/pers)	None	1010	0.112	779.0	0.076	169.1	0.131	180.1	0.037	258.0	0.037
	Express	1009	0.102	775.5	0.077	164.8	0.102	178.9	0.034	262.0	0.034
	Arterial	1007	0.104	758.7	0.074	174.5	0.118	183.7	0.028	259.7	0.028
	All	1038	0.126	769.0	0.086	163.2	0.137	193.4	0.128	269.3	0.127
Delays (sec/pers)	None	628.0	0.122	485.3	0.115	114.7	0.180	91.5	0.048	142.1	0.048
	Express	626.3	0.118	481.5	0.116	110.4	0.134	90.2	0.035	143.4	0.035
	Arterial	626.7	0.114	464.7	0.113	120.6	0.158	95.5	0.041	144.3	0.041
	All	653.0	0.144	474.5	0.122	107.3	0.171	102.5	0.161	151.1	0.159
Vehicle Stops	None	20.97	0.108	17.68	0.044	3.05	0.055	2.45	0.013	4.26	0.013
	Express	21.17	0.085	17.62	0.043	3.04	0.055	2.44	0.010	4.35	0.010
	Arterial	20.95	0.100	17.50	0.042	3.04	0.056	2.49	0.012	4.28	0.012
	All	20.90	0.080	17.57	0.049	3.02	0.056	2.52	0.024	4.31	0.024
Fuel Consumption (L/km)	None	0.225	0.109	0.230	0.044	0.240	0.064	0.160	0.011	0.161	0.011
	Express	0.226	0.089	0.230	0.043	0.238	0.059	0.160	0.009	0.161	0.009
	Arterial	0.224	0.099	0.228	0.042	0.242	0.065	0.162	0.010	0.163	0.010
	All	0.225	0.089	0.229	0.050	0.237	0.060	0.164	0.032	0.165	0.032
HC Emissions (g/km)	None	1.041	0.138	1.064	0.056	0.993	0.073	0.531	0.007	0.537	0.007
	Express	1.044	0.109	1.066	0.054	0.997	0.078	0.532	0.005	0.537	0.005
	Arterial	1.033	0.119	1.057	0.052	0.987	0.077	0.533	0.006	0.539	0.006
	All	1.010	0.109	1.068	0.062	1.011	0.078	0.534	0.008	0.539	0.008
CO Emissions (g/km)	None	30.67	0.138	32.11	0.056	29.73	0.071	15.01	0.006	15.19	0.006
	Express	30.79	0.106	32.16	0.055	29.94	0.078	15.03	0.005	15.21	0.005
	Arterial	30.42	0.116	31.91	0.053	29.52	0.076	15.05	0.006	15.22	0.006
	All	29.72	0.104	32.22	0.062	30.50	0.079	15.01	0.008	15.18	0.007
NOx Emissions (g/km)	None	0.699	0.114	0.714	0.043	0.691	0.055	0.443	0.007	0.446	0.007
	Express	0.706	0.090	0.712	0.041	0.692	0.056	0.443	0.006	0.446	0.006
	Arterial	0.697	0.103	0.708	0.041	0.691	0.056	0.446	0.006	0.449	0.006
	All	0.691	0.083	0.712	0.048	0.689	0.057	0.448	0.011	0.451	0.011

TABLE 3 Simulated Performance Measures for Midday Scenarios with 5-second green extension interval

Measure	Buses With Priority	Regular Buses		Cross-Street Buses		Cars		All Traffic	
		Mean	Variance	Mean	Variance	Mean	Variance	Mean	Variance
Travel Time (sec/pers)	None	808.9	0.049	119.5	0.069	122.4	0.006	162.0	0.006
	Arterial	783.3	0.057	119.9	0.062	122.6	0.006	160.8	0.006
	All	784.3	0.059	107.0	0.067	123.2	0.006	160.6	0.006
Delays (sec/pers)	None	499.3	0.080	72.0	0.102	49.4	0.008	74.6	0.008
	Arterial	473.7	0.092	72.5	0.094	49.6	0.009	73.5	0.009
	All	474.7	0.095	59.8	0.114	50.2	0.009	73.4	0.009
Vehicle Stops	None	20.51	0.036	2.78	0.050	2.07	0.007	3.09	0.007
	Arterial	20.38	0.040	2.77	0.050	2.07	0.007	3.08	0.007
	All	20.40	0.041	2.66	0.050	2.08	0.007	3.08	0.007
Fuel Consumption (L/km)	None	0.240	0.033	0.217	0.042	0.148	0.006	0.149	0.006
	Arterial	0.237	0.037	0.217	0.043	0.148	0.007	0.149	0.006
	All	0.238	0.038	0.210	0.038	0.149	0.006	0.149	0.006
HC Emissions (g/km)	None	1.340	0.057	1.078	0.054	0.602	0.008	0.606	0.008
	Arterial	1.332	0.064	1.080	0.062	0.601	0.008	0.605	0.008
	All	1.334	0.066	1.080	0.056	0.602	0.007	0.606	0.007
CO Emissions (g/km)	None	39.91	0.055	32.52	0.054	17.39	0.008	17.52	0.008
	Arterial	39.77	0.061	32.53	0.063	17.38	0.008	17.50	0.008
	All	39.84	0.063	32.77	0.056	17.39	0.007	17.51	0.007
NOx Emissions (g/km)	None	0.771	0.037	0.661	0.044	0.435	0.007	0.437	0.007
	Arterial	0.767	0.039	0.661	0.047	0.435	0.007	0.437	0.007
	All	0.768	0.040	0.652	0.043	0.436	0.007	0.438	0.007

TABLE 4 Impacts of Transit Priority Scenarios on Performance Measures

Measure	Buses With Priority	AM					Midday			
		Express Buses (%)	Arterial Buses (%)	Cross Buses (%)	Cars (%)	All Traffic (%)	Arterial Buses (%)	Cross Buses (%)	Cars (%)	All Traffic (%)
Travel Time	Express	**-0.05**	**-0.45**	-2.51	-0.64	-0.67				
	Arterial	-0.28	**-2.61**	3.23	**1.99**	1.23	**-3.17**	0.29	0.12	**-0.76**
	All	2.82	-1.28	-3.48	**7.41**	**5.70**	**-3.05**	**-10.51**	**0.63**	**-0.84**
Person-Delays	Express	**-0.27**	**-0.77**	-3.75	-1.39	-1.36				
	Arterial	-0.21	**-4.23**	5.16	**4.43**	**2.74**	**-5.13**	0.64	**0.35**	**-1.48**
	All	3.99	-2.22	**-6.42**	**12.03**	**8.70**	**-4.93**	**-16.99**	**1.59**	**-1.64**
Vehicle Stops	Express	0.94	**-0.34**	-0.10	-0.35	**0.34**				
	Arterial	-0.12	**-1.04**	-0.36	**1.63**	**0.86**	**-0.63**	-0.46	**-0.05**	**-0.44**
	All	-0.35	-0.67	**-0.89**	**2.82**	**1.75**	**-0.57**	**-4.16**	**0.30**	**-0.41**
Fuel	Express	0.47	-0.19	-0.65	-0.20	-0.20				
	Arterial	-0.19	**-1.06**	0.92	**1.11**	**1.08**	**-1.09**	0.18	**0.01**	**0.00**
	All	-0.12	-0.41	**-1.28**	**2.50**	**2.45**	**-1.01**	**-3.04**	**0.21**	**0.20**
HC	Express	0.30	0.19	0.40	0.08	0.08				
	Arterial	-0.76	-0.67	-0.58	**0.42**	**0.39**	**-0.59**	0.15	**-0.09**	**-0.10**
	All	**-2.99**	0.36	**1.84**	**0.49**	**0.48**	-0.40	**0.15**	**-0.01**	**-0.02**
CO	Express	0.37	0.15	**0.71**	0.11	0.11				
	Arterial	-0.83	-0.63	-0.73	**0.25**	**0.22**	-0.35	0.03	**-0.10**	**-0.10**
	All	**-3.09**	0.35	**2.57**	-0.03	-0.03	-0.17	0.76	**-0.03**	**-0.03**
NOx	Express	1.00	-0.16	0.15	0.04	0.04				
	Arterial	-0.29	**-0.71**	0.02	**0.81**	**0.79**	**-0.48**	0.01	**-0.05**	**-0.06**
	All	-1.14	-0.22	-0.28	**1.23**	**1.20**	**-0.43**	**-1.36**	0.12	0.11

* Numbers in bold indicate statistically significant change at 95% confidence level

TABLE 5 Effect of Changing Green Extension Interval Duration

Green Extension Interval	Columbia Pike Buses				Cars			
	Travel time (sec/pers)	Delay (sec/pers)	Stops	Fuel (L/km)	Travel Time (sec/pers)	Delay (sec/pers)	Stops	Fuel (L/km)
AM Peak								
2 sec	758.2	96.10	17.50	0.228	189.7	96.10	2.49	0.16
3 sec	763.6	97.90	17.51	0.228	184.6	97.90	2.50	0.16
4 sec	765.1	97.65	17.53	0.228	186.4	97.65	2.50	0.16
5 sec	758.7	95.53	17.50	0.228	187.5	95.53	2.49	0.16
6 sec	755.6	95.18	17.49	0.228	183.7	95.18	2.48	0.16
10 sec	766.8	96.43	17.54	0.229	183.0	96.43	2.48	0.16
Midday								
2 sec	788.0	506.2	20.30	0.235	126.8	53.81	2.14	0.150
3 sec	788.7	478.6	20.12	0.234	126.8	53.85	2.14	0.150
4 sec	784.5	479.4	20.28	0.235	126.8	53.80	2.14	0.150
5 sec	782.4	475.0	20.07	0.235	126.7	53.75	2.14	0.150
6 sec	783.4	476.6	20.38	0.237	122.5	49.57	2.07	0.148
10 sec	785.0	473.8	20.39	0.238	122.4	49.48	2.07	0.148

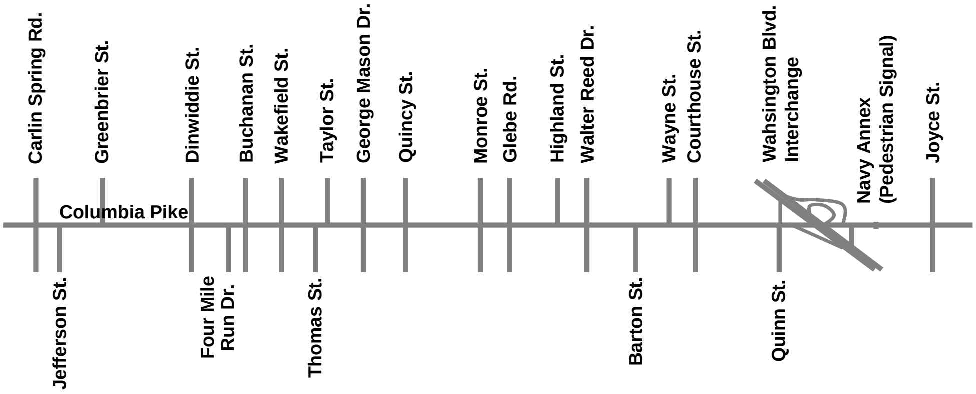

FIGURE 1 Study corridor.

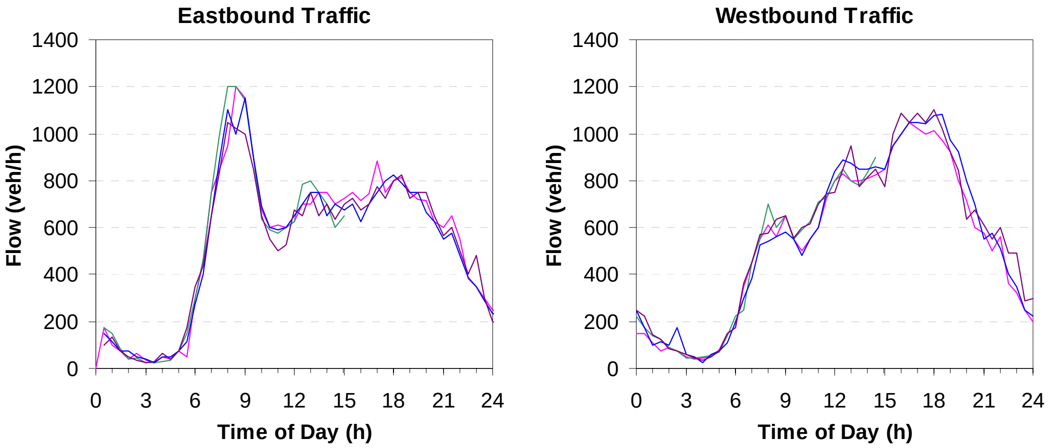

FIGURE 2 Average 15-minute traffic flow rates observed at the intersection with George Mason Dr. on June 12-14, 2000.

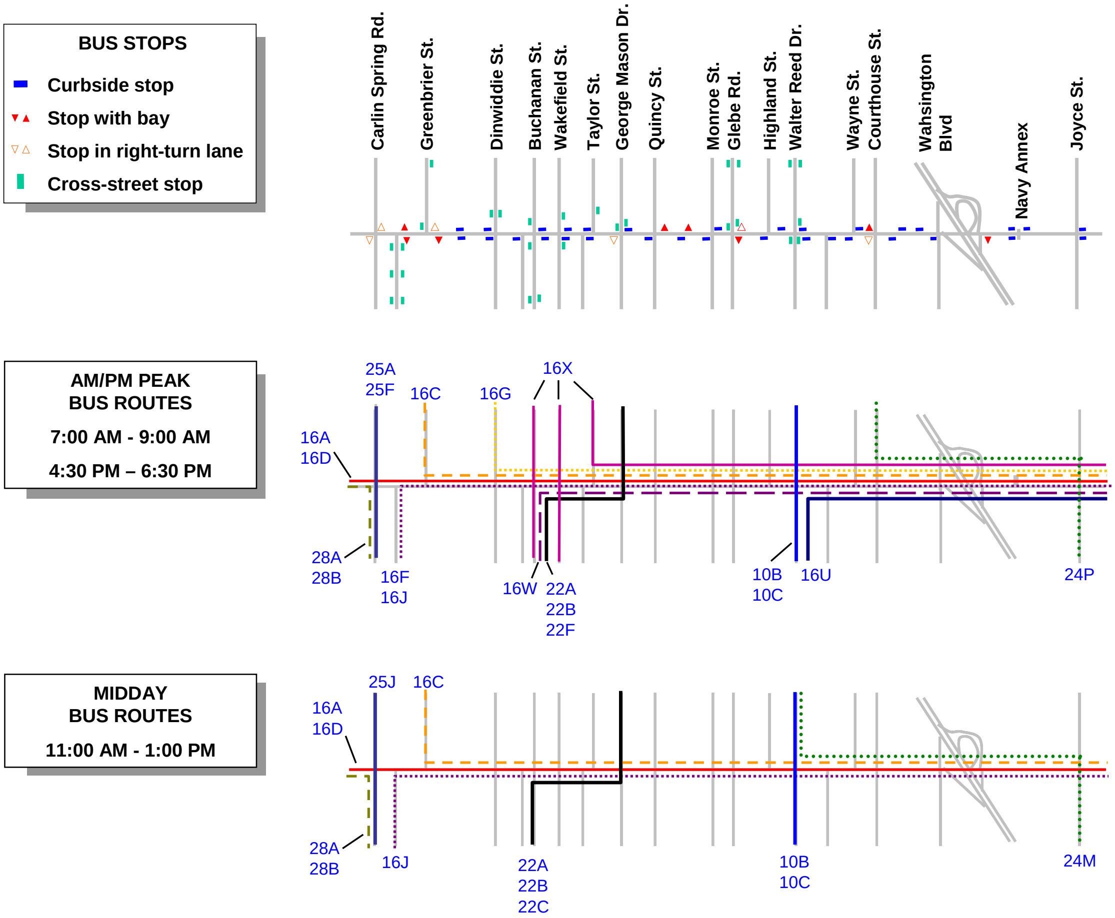

FIGURE 3 Transit service along study corridor.

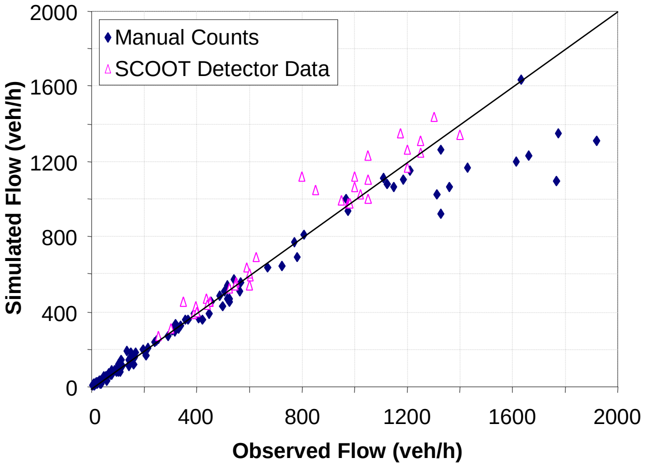

FIGURE 4 Observed and simulated flow comparison for 8:00-8:15 AM peak interval.