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EVALUATION OF SERVICE RELIABILITY IMPACTS OF TRAFFIC SIGNAL PRIORITY STRATEGIES FOR BUS TRANSIT

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ABSTRACT

Recent progress in technology has facilitated the design, testing, and deployment of traffic signal priority strategies for transit buses. However, a clear consensus has not emerged regarding the evaluation of these strategies. Each agency implementing these strategies can have differing goals, and there are often conflicting issues, needs, and concerns among the various stakeholders. This research attempts to assist in the evaluation of such strategies by presenting an evaluation framework and plan that provides a systematic method to assess potential impacts. The use of this framework and plan is illustrated on the Columbia Pike corridor in Arlington, Virginia using the INTEGRATION simulation package. In building upon prior efforts on this corridor, this work presents a method of simulating conditional priority to late buses to investigate the impacts of priority on service reliability. Using the measures developed in this research, a conditional priority strategy designed to increase bus service reliability without resulting in severe traffic-related impacts was tested. Simulation results indicated statistically significant improvements of 3.2% in bus service reliability and 0.9% for bus efficiency, while negative traffic-related impacts were found in the form of increased overall delay to the corridor of 1.0% on a vehicle basis or 0.6% on a person basis. These results are also comparable and consistent with the results of other research as reported in this paper.

INTRODUCTION

Although traffic signal priority strategies for transit have existed for more than two decades, there has been a great deal of recent interest in new applications, and a shift of some attitudes towards re-examining the use of priority. In part due to advances in technologies, jurisdictions have now been able to examine and deploy traffic signal priority for transit vehicles in a variety of different areas using different detection systems and architectures (*1*).

There is a need for an evaluation framework and plan which can be used to determine the impacts associated with various traffic signal priority strategies as applied to transit. This evaluation framework and plan can provide a systematic basis for stakeholders to examine the likely impacts of potential deployments and to assess the degree to which they achieve desired objectives. In particular, the extent to which traffic signal priority strategies can improve the service reliability of bus operations warrants investigation. This research formulated an evaluation framework and plan for traffic signal priority strategies for transit, and illustrated their application in an assessment of transit service reliability impacts in a simulation of the Columbia Pike corridor in Arlington, Virginia.

LITERATURE REVIEW

Objectives of Transit Signal Priority

Stakeholders in a Washington, D.C. Case Study (*2*) suggested four policy requirements for priority systems. They are presented here in the order in which they were mentioned.

1. The system shall improve schedule adherence.
2. The system shall improve the efficiency with which buses run, reducing operating costs and allowing greater schedule flexibility.
3. A priority system shall be part of a larger ITS system that includes improved rider information and other services.
4. Priority shall increase the overall efficiency with which the road network is used by contributing to an increasing in bus ridership.

In past deployments, the objectives varied somewhat, but typically emphasized improving the quality of transit service and/or the efficiency of operations. By potentially improving schedule adherence, a priority system can improve the quality of transit service and enhance mode share. Service unreliability can have a great impact on ridership, by increasing the uncertainty and anxiety to passengers (*3*). Noland et al (*4*) found that costs associated with uncertainty resulted primarily from costs of early or late arrival.

Deployment Experience

Table 1 highlights the reported results from several past and in-progress deployments of signal priority for transit in North America. In addition, much progress has been made in transit priority outside the U.S., but the institutional structure and policies are often quite different, such that care should be taken with comparisons. However, an example from Eindhoven, Netherlands (*5*) illustrates a key attribute of a more sophisticated implementation, conditional priority. In the Eindhoven implementation, buses were given priority only if they were running late, in an attempt to provide operational control for buses to maintain schedule adherence. As compared with no priority, the conditional priority had little impact on vehicle delay while improving schedule adherence.

Transit Priority Evaluation using Simulation

Beyond the evaluations conducted on field deployments and operational tests, several efforts have been made to evaluate transit signal priority using simulation and other analytic approaches.

In 1996, Khasnabis et al (*6*) used the NETSIM simulation model to evaluate a hypothetical bus corridor with priority. However, since NETSIM did not provide the capability for signal priority, the researchers visually tracked the buses using the graphical display tool, and determined whether the bus would be granted priority accordingly. The delay output measures from NETSIM were then adjusted for assumed vehicle occupancy and the resulting person-minutes of delay was used as the evaluation measure. The test corridor evaluated indicated a decrease in delay along the main (priority) direction while the cross streets had an increase in delay. Bus travel time with priority decreased by a range of 0.3 to 13.5 percent as compared to the base.

Garrow and Machemehl (*7*) attempted to use NETSIM to establish what conditions tend to be favorable and unfavorable for transit priority. Unconditional priority was simulated in a similar fashion as Khasnabis et al (*6*), under various scenarios. Delay on a vehicle basis served as the primary evaluation measure in their analysis, while selected scenarios also examined bus and auto travel times, and delay weighted by vehicle occupancy. The results from this study suggested that degree of saturation plays a key role in the delay impacts when transit vehicles are given priority.

Signal priority for transit attempts to improve the quality of service and/or efficiency of transit operation while considering potential detrimental effects on other traffic. While schedule adherence is a common element of quality of service, it has not been measured often in prior experience. More frequently, bus travel time savings, representing another quality of service element and efficiency improvement, have been used as the general metric for benefit to transit. Past deployment experiences with priority for transit have generally been positive, with minimal delay for other traffic, and improvements in travel time for transit buses. However, given the varying situations that exist in deployments, caution should be exercised in generalizing results. In particular, variables such as the level of saturation, coordination transition algorithms, and priority criteria, are not uniform across the various deployments. These considerations play an important role in the implementation of signal priority and the nature of benefits and impacts.

RESEARCH APPROACH

An evaluation framework and plan that may be used in the assessment of alternative traffic signal priority strategies for bus transit was developed as part of this research (*8*). The framework (see Figure 1) centers on the evaluation plan, which considers objectives of stakeholders and the environment surrounding traffic signal priority in order to isolate positive and negative effects of traffic signal priority under various conditions. The various traffic signal priority strategies are an “input” to the evaluation process, while the “output” consists of the performance of each strategy. The central element of the framework, the evaluation plan, specifies how the performance of each strategy would be quantified in terms of meeting stated objectives within the specific environment.

Evaluation Plan

The evaluation plan embodies the measurement of performance impacts resulting from various traffic signal priority strategies. Appropriate measures of effectiveness, both quantitative and qualitative, can be established for each system objective to be evaluated. For example, service reliability may be measured by on-time performance (OTP), which gauges the frequency of arriving outside certain time thresholds relative to the scheduled timepoint. This research has conceptualized and developed measures of effectiveness (*8*) corresponding to differing objectives of transit signal priority (see Table 2), as the evaluation framework suggests.

Application to Service Reliability

The evaluation framework and plan are applied in this research to the evaluation of bus service reliability impacts using field and simulation data from the Columbia Pike corridor in Arlington, Virginia, building upon prior work by Dion et al (*9*) and Zhang (*10*). This base network had been constructed in the INTEGRATION simulation package, which provides strength in modeling of individual vehicles on a second by second basis, as well as a signal priority feature that is selectable by vehicle class and intersection. Since the operation of priority depends on the location and travel of the buses, precise location and tracking is necessary for analysis. INTEGRATION was used in conjunction with the QueensOD model, which provided the means to calibrate the INTEGRATION model. INTEGRATION uses a zonal origin-destination matrix; QueensOD utilized the observed data from field traffic counts at intersections and traffic detectors to provide INTEGRATION with the required zonal flows. The geometric data, fixed signal timings, and bus stop locations were provided by Arlington County Department of Public Works, while speed data was collected using a GPS-equipped vehicle. Although the corridor currently uses the SCOOT signal system, the fixed timings provided had recently been optimized. Given the particular conditional priority strategy tested in this research, it was necessary to use the simple fixed timing plans as they provided repeatability over multiple runs, whereas SCOOT may alter the timings in successive runs. Transit data was based on a combination of published schedules and field data collection of occupancy, travel time, and dwell times. It is important to note that INTEGRATION provides limited modeling capabilities for transit operations, and therefore, simplifying assumptions, such as buses servicing each stop with a uniform dwell time, were necessary.

In the illustration of the evaluation plan, a specific situation will be examined, namely the AM peak period for buses traveling east on Columbia Pike. Columbia Pike is a radial arterial connecting inner suburbs with the Pentagon and access to Washington, DC. Within the study area, a 6 km (4-mile) segment in Arlington, frequent local bus service and peak limited-stop service is operated by Metrobus. Primarily, the services connect various neighborhoods with the Columbia Pike corridor and the Pentagon. Significantly, at the Pentagon, a major intermodal transfer center provides connections to buses and Metrorail trains.

The measures of effectiveness to be used were selected from Table 2, and were chosen to represent passengers who board eastbound buses destined for the Pentagon as either a final destination or transfer point.

Given that many of the trips are work trips, the bus service reliability measure selected was arrival reliability, since workers are generally trying to arrive to work at the same time each day. With the large number of transfers at the Pentagon bus/rail station, the significance of arrival time is magnified, since missing a transfer often translates into a relatively long wait time for the next bus or train. These passengers may be able to adjust to somewhat longer or shorter travel times, as long as they are consistent. However, if travel times vary greatly, passengers are likely to add additional planned travel time by leaving early enough to arrive on-time most of the time, or select a different mode. In terms of bus efficiency, the measure to be used is the averaged Running Time between two selected points. Finally, the impact on other traffic will be evaluated based on impacts on overall delay in the corridor, both on a person and vehicle basis. Since stakeholders are averse to creating significant adverse impacts on other traffic, changes in average delay are important to examine.

The selection of these measures under the given conditions on the Columbia Pike corridor give rise to the following hypotheses which were examined, using INTEGRATION:

Hypothesis # 1. The provision of priority to eastbound buses that are late will be associated with higher *bus service reliability*.

Hypothesis # 2. The provision of priority to eastbound buses that are late will be associated with higher *bus efficiency*.

Hypothesis # 3. The provision of priority to eastbound buses that are late will be associated with *other traffic-related impacts* such as increased overall delay.

RESULTS

The results illustrate the assessment of a scenario of a "catch up" priority strategy for eastbound buses on Columbia Pike in the AM peak period, using INTEGRATION. In the "catch up" priority strategy, a single checkpoint is used to establish whether a particular bus is behind schedule by more than a certain threshold. If so, the bus is given priority for the remaining portion of the corridor, in order to "catch up" to its schedule. Since INTEGRATION does not currently have direct support for real-time conditional priority, this "catch up" strategy was selected as a compromise that provides conditional priority yet entails a reasonable level of complexity in implementation. At the same time, the strategy has a practical basis in operations by attempting to address the problem of late buses through the use of conditional priority. The checkpoint selected for this analysis is the intersection of Columbia Pike and George Mason Drive, chosen primarily to balance the data requirements for the simulation. The endpoint of the segment, Columbia Pike at the Navy Annex, was selected based on the availability of a scheduled timepoint near the end of the corridor. Overall, this segment covers 3.7 km (2.3 miles) of the test corridor, and 36 bus trips are scheduled over this segment during the AM peak.

The threshold for determining whether a bus is sufficiently behind schedule to warrant the "catch up" priority was estimated based on the priority logic in the INTEGRATION simulation model and the characteristics of the priority segment. However, such as strategy should not make the bus get ahead of schedule as a result of receiving priority treatment. Therefore, the threshold is set to a value approximating the total maximum additional green time for a bus receiving priority. In this way, a bus would need to be sufficiently behind schedule at the threshold so as not to arrive at the destination early even if receiving the maximum benefit from priority. Based on the signal timings, 150 seconds was estimated as the practical maximum benefit, so buses which arrive more than 150 seconds later than the scheduled time at Columbia Pike and George Mason Drive are given priority for the remainder of the corridor.

Simulation Process

The simulation process used in this research builds upon prior work by Dion, Rakha and Zhang (*9*). Their INTEGRATION model network of the Columbia Pike corridor was used as a base network upon which testing was conducted. Since INTEGRATION currently does not provide real-time priority, a method was developed for using the existing class-based priority mechanism. Due to limitations in the vehicle classes available, cross street buses were recoded as local buses so that an additional vehicle class would be available for priority buses. This "priority class" was configured as eligible for priority on signals from George Mason Dr. to the Navy Annex. In order to activate priority for a particular bus, the bus would be reclassified into the "priority class" vehicle type prior to executing the simulation. However, in order to determine which buses were eligible for priority based on the lateness threshold, it was necessary to first execute the simulation without priority and analyze the bus operations. The arrival times of buses at George Mason Dr. were compared with the scheduled times, yielding the lateness to be compared with the threshold. Hence, each simulation run needed to be executed at least twice for each random number seed.

Postprocessing of the output from the simulation was conducted external to INTEGRATION, using Microsoft Excel. INTEGRATION can provide time and other information when designated vehicles complete an individual network link. This data was imported into Excel and filtered to find the eastbound buses of interest. Then, the simulation times for each bus were extracted for George Mason Dr. and Navy Annex. These times were compared with the scheduled timepoints at these locations, and by subtraction, the arrival time "delta" (representing lateness) was calculated. In the non-priority (first) case, the lateness at the threshold location (George Mason Dr.) was used to determine which buses would receive priority. In addition, the endpoint lateness was also captured in order to provide a basis for comparison with the priority case. After recoding the input files to reclassify the vehicle class for priority buses, the simulation process was repeated. In this priority (second) case, the calculation of arrival time delta was made at the endpoint (Navy Annex). By computing the standard deviation of these lateness values, the selected measure of bus service reliability was generated. In order to capture running time for use in measuring bus efficiency, the same simulation times at George Mason Dr. and Navy Annex were used, with the difference representing the running time between the endpoints. Finally, the simulation summary file with aggregate traffic measures including delay was saved and postprocessed to extract overall delay by vehicle class.

Relationship with hypotheses

The application of the "catch up" priority strategy attempts to illustrate the presence of a relationship between the priority condition, being behind schedule by at least a certain amount, and bus service reliability. In particular, this analysis attempts to establish a relationship between the priority strategy and the signal delay experienced by buses. By selecting buses for priority treatment using the lateness criteria, overall bus service reliability may be increased, as the first hypothesis states. In addition, by reducing the signal delay, the bus efficiency would also be increased, as stated in the second hypothesis. Finally, the third hypothesis suggests that the priority given will have other traffic-related impacts due to the changes in signal timing resulting from priority.

Bus Service Reliability – Arrival Reliability

Based upon the capabilities of INTEGRATION and the priority strategy being tested, the measure selected for bus service reliability is arrival reliability (Measure 1.5 from Table 2). In the test scenario, buses begin at varying origin points since there are several interlined routes. Arrival reliability may be quantified by the standard deviation of the arrival time delta or lateness (the difference between actual and scheduled arrival time) at the endpoint, Columbia Pike at the Navy Annex. If buses arrive very close to the scheduled arrival time, the standard deviation would be low, and arrival reliability would be high. Conversely, if buses arrive much earlier and later than the scheduled time, arrival reliability would be low. However, further clarification of an exception to this statement is warranted. If buses arrive consistently late or early by a certain amount, the arrival reliability could be high, even if the degree of earliness or lateness is significant. The reasoning in this case is that the service may be reliable, but the schedule may not reflect arrival times accurately.

Individual Trip Level Analysis

By applying the measure of arrival reliability at the level of a specific scheduled trip (e.g. the trip scheduled to depart George Mason Dr. at 8:22 a.m.), the impact of priority for riders who regularly ride at that time may be examined. The running time from George Mason Dr. to the Navy Annex was examined for a particular scheduled trip (e.g. the trip departing George Mason Dr. at 8:22 a.m.), scheduled to depart at 1350 seconds into the simulation. Based on 30 simulation runs, the arrival reliability of this trip, measured by the standard deviation of the "delta" at the Navy Annex, was 340.8 seconds in the base case, and 325.7 seconds with priority active, representing a 4% decrease. This increase in arrival reliability was found to be statistically significant using the paired two-sample t test for means with a p value of 0.039.

Analysis of Reliability over a Period of Time

Schedule reliability may be examined across the peak period, rather than looking at individual scheduled trips. By using the measure of arrival reliability, quantified by the standard deviation of the difference between arrival time and scheduled time, one can get a picture of the bus service reliability over a time period. As the standard deviation decreases, the arrival time becomes more consistent. Though there may be an offset versus a printed schedule, this may be remedied in a consistent service by adjusting the timetable, or otherwise regular riders would become accustomed to the offset. Ideally, the offset, represented by the mean deviation from schedule, would approach zero as the standard deviation narrows, but may be a tradeoff in preventing buses from getting ahead of schedule.

Bus Service Reliability – Hypothesis #1

In the case of the test segment on Columbia Pike from George Mason Drive to Navy Annex, the arrival reliability (Measure 1.5 from Table 2) represented by the standard deviation of arrival time "delta", or difference between actual and scheduled time, was calculated at Navy Annex for eastbound buses. The resulting values for the 30 pairs of simulation runs without and with priority are shown in Figure 2. In 23 of the 30 cases, the provision of priority resulted in a lower standard deviation, representing greater bus service reliability. Overall there was an average decrease of 3.2% in the standard deviation of arrival time delta, from 209 to 202.4 seconds. Using the paired two-sample t test for means, this difference was found to be statistically significant with a p value of 0.003. This indicates that the arrival reliability is higher with conditional priority than with no priority, affirming Hypothesis #1, which states that the provision of priority will be associated with higher bus service reliability.

Aggregating the data from the 30 simulation runs depicted in Figure 2, the effect of priority on arrival reliability (Measure 1.5 from Table 2) can also be visualized in a smoothed frequency chart of arrival time delta, as shown in Figure 3. The arrival reliability relates graphically to the "narrowness" and height of the curve, which corresponds to the same measure used previously, the standard deviation of arrival time delta. Ideally, the curve would be represented by an impulse function, located at the exact scheduled time, i.e. 0 minutes behind schedule. In reality, the most desirable distributions have a steep cutoff at 0 minutes, meaning few early buses, a tall peak immediately after, representing arrivals on time and immediately after, and again a steep cutoff downward near as possible to the 0 point, representing few buses that are significantly behind schedule. Improved arrival reliability would result in a lower standard deviation of arrival time delta, and a narrower and taller, and hence more desirable, frequency distribution chart. The "catch up" priority treatment for late buses appears to narrow the distribution of arrival time delta by a small amount, consistent with the prior results in terms of standard deviation.

A Comparison with Autos (Time Reliability)

As a reference for comparison of variability in travel times, a sampling of probe vehicles, consisting of normal autos, was specified for the 30 base simulation runs in INTEGRATION. The arrival times for these vehicles were captured at the two timepoints at George Mason Dr. and the Navy Annex, just as bus arrival times were captured. However, since autos do not have a schedule, Time Reliability (Measure 1.2 from Table 2) was used for analysis. Travel times were calculated based on these arrival times, and the standard deviations of these travel times for each simulation run were computed. Averaging the data for the 30 simulation runs, the average standard deviation was found to be 41.9 seconds. Comparing to the corresponding value for buses in the base case, 157.7 seconds, the results indicate substantially less variability in travel time for autos as compared to buses. This is consistent with the prior discussion of the four factors impacting bus reliability. Autos and buses would generally have similar exposure to the factors of signal delay (in the base case) and traffic-related delay. However, buses are exposed to the significant factor of dwell time, which is likely to be highly variable due to passenger demand and loading variations. For example, a limited sample of field data from Columbia Pike indicated a coefficient of variation for dwell times of 0.7 (*10*).

Bus Efficiency – Average Running Time

In terms of bus efficiency from an operational perspective, the 95th-percentile running time (Measure 2.2 from Table 2) can provide a good indication of potential performance in terms of bus schedules. If a particular trip may be completed in a shorter time on a consistent basis, there exists the potential for operational savings. However, one reliability measure is already being considered; also, in order to get a good estimate of the 95th-percentile running time, it is desirable to complete a large number of simulation runs since each provides only one observation for any particular bus trip, and the potential for a fewer number of samples to skew the result is substantial.

Bus Efficiency – Hypothesis #2

Meanwhile, the average running time (Measure 2.1 from Table 2) can be used for scheduling by considering it along with applicable recovery/layover time. For passengers, changes in mean running time without priority and with priority should provide evidence of potential direct travel time benefits. Figure 4 shows the average bus running times for the test segment for the 30 simulation run pairs. In 20 of the 30 cases, the average running time was lower in the case with priority. Overall, a 0.9% decrease in travel times was observed on average over the segment when "catch up" priority was granted, from 552.6 to 547.8 seconds. Using the paired two-sample t test for means, this difference was found to be statistically significant with a p value of 0.015. This indicates that the average bus running time is lower with conditional priority than with no priority, affirming Hypothesis #2, which states that the provision of priority will be associated with higher bus efficiency.

Other Traffic-Related Impacts – Overall Delay (person, vehicle)

Other traffic-related impacts resulting from the use of transit signal priority play a critical role in the evaluation process. Some important stakeholder groups tend to be more cognizant of potential negative impacts on the general motoring public than potential benefits to transit users and operators. The ability to quantify these potential impacts using simulation is a key part of the evaluation plan.

Other Traffic-Related Impacts – Hypothesis #3

The INTEGRATION simulation model contains built-in measurement tools to assess changes in delay, emissions, and other similar impacts. In this case of evaluating transit signal priority, two measures relating to Overall Delay (Measure 3.1 from Table 2) were selected to reflect the other traffic-related impacts. Overall vehicle delay on the corridor captures the aggregate delays experienced by all vehicles. Given the same underlying conditions, the simulations without and with priority may be compared to estimate average changes in delay per vehicle. Figure 5 shows the results from the 30 simulation run pairs. In 21 of the 30 cases, the average delay per vehicle was higher when priority was given. Overall, there is an average increase in vehicle delay of 1.0% with priority, from 86.5 seconds to 87.4 seconds per vehicle. Using the paired two-sample t test for means, this difference was found to be statistically significant with a p value of 0.003. This indicates that the overall delay on a vehicle basis is higher with conditional priority than with no priority, affirming Hypothesis #3, which states that the provision of priority will be associated with other traffic-related impacts such as increased overall delay.

Another way to analyze the impacts that transit signal priority has on other traffic is to examine the average change in delay experienced by each individual person traveling in the corridor. Since buses typically carry a much higher passenger load than other vehicles, the delay impact on buses is magnified relative to other vehicles. Based on field data, the average occupancy for buses was assigned a value of 23 passengers, while other traffic was given an average occupancy of 1.1. Figure 6 shows the results after weighting the delay amounts by number of passengers. Overall, the net average increase in person delay over the corridor is 0.6% when priority is granted, from 104.4 to 105.1 seconds per person. Using the paired two-sample t test for means, this difference was found to be statistically significant with a p value of 0.021. This indicates that the overall delay on a person basis is higher with conditional priority than with no priority, affirming Hypothesis #3, which states that the provision of priority will be associated with other traffic-related impacts such as increased overall delay. Given the average occupancies in this case, the aggregate reduction in delay to passengers on buses was less than the aggregate delay increase to users of other vehicles in this priority scenario.

SUMMARY / CONCLUSIONS / RECOMMENDATIONS

Summary

This research resulted in the development of an evaluation framework and plan that assesses the impacts of signal priority strategies for transit buses. Three major categories of impacts were considered:

- Effects on Bus Service Reliability
- Effects on Bus Efficiency
- Other Traffic-Related Impacts

Within these categories, a variety of indicators were proposed, each measuring a different aspect of impact. Depending on the particular environment and objectives, the most appropriate measures of effectiveness could be chosen from the proposed measures.

The application of the framework and plan was illustrated through its application on the Columbia Pike corridor in Arlington, Virginia, using the INTEGRATION simulation package. A specific strategy was considered in this analysis, namely a "catch up" provision for eastbound buses in the AM peak period. This provision had the intended goal of lessening the lateness of buses at the destination by offering conditional priority to buses that were late at a certain checkpoint. The priority status was continued for late buses until the end of the corridor. The priority given to buses consisted of extending the green indication on the main street (Columbia Pike) up to a certain limit, or providing an early green indication, again up to a limit.

INTEGRATION was used to model the movement of vehicles and provide priority through an external computer-assisted conditional priority method developed in this research. The method involves using the simulation to determine which buses would be late at the checkpoint, and assigning the late buses to a different vehicle class which would be then be given priority in a new simulation run. Results were tabulated and analyzed with the use of the Microsoft Excel spreadsheet package.

Conclusions

Under the given conditions, the results indicated a statistically significant change in each of the selected impact measures when conditional priority was granted to the late eastbound AM peak buses:

- A 3.2% improvement the bus service reliability, as measured by arrival reliability in the form of standard deviation of arrival time delta, was found.
- In terms of bus efficiency, a 0.9% decrease in running time, also statistically significant, was observed when transit buses were given conditional priority.
- An average 1.0% increase in vehicle delay, or a 0.6% increase in terms of person delay, was found for all vehicles and persons traveling on the corridor.

These impacts are consistent with prior expectations as well as results from transit signal priority field deployments (see Table 1), keeping in mind that only buses designated as late were given priority. In this situation, a transit signal priority strategy granted on a conditional basis is associated with improvements in bus service reliability and bus efficiency. Since the late buses should have a reduced travel time as a result of priority, they should arrive at the endpoint closer to the scheduled time. The provision of extended green and early green to priority buses also tends to reduce travel time for those buses and therefore the average for all buses. While the absolute magnitude of the travel time savings (0.9%) is small, it is important to note that the primary objective of the "catch-up" strategy is not to make transit travel time faster, but *more reliable*. At the same time, when conditional priority is granted, an increase in delay to other travelers is found, though the average magnitude is small. Since the signal timing plan attempts to optimize the efficiency of overall vehicular traffic, changes to the signal timings resulting from priority would tend to move the timings away from the optimal state, thereby increasing vehicle delay. Given the higher occupancy of the buses that benefit from priority, the observed lesser impact on person delay is expected. In addition, to the extent that service improvements resulting from priority increase bus ridership and occupancy, overall impacts on person delay should also improve.

This research has also built upon the analysis of Dion, Rakha, and Zhang (*9*), which examined the use of unconditional priority on the same corridor. Buses in selected classifications (e.g. local buses, express buses, cross street buses, and combinations) were given priority at all intersections without regard to lateness, occupancy, or other bus dependent factors; however, the priority functionality in INTEGRATION contains internal conditions such as minimum green times and a limit of one activation per cycle. On the same corridor during the same time period, but with unconditional priority for regular buses along Columbia Pike, the prior study found a 6% decrease in travel time for buses, an 8% increase in overall person-delay. A comparison with the results of this research must be considered carefully given the substantially different degree of priority; however, the results indicate that a “lesser” (i.e., conditional) priority strategy yielded a smaller decrease in bus travel time, and a smaller increase in overall person-delay.

The technique developed in this research to institute conditional priority using a computer-assisted technique external to INTEGRATION may be extended to examine other cases along the “spectrum” between no priority and full unconditional priority in order to gain a better understanding of the relationship. The small nominal impacts found in this research suggest that the priority strategy selected, "catch-up", under the given conditions, falls close to the no priority part of the spectrum, yet was able to demonstrate measurable and statistically significant impacts, lending support to the evaluation framework and plan. In addition, the impact on service reliability was shown to be greatest of the impacts measured, results in line with the primary objective of the tested strategy.

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TABLE 1 Summary of Transit Signal Priority Field Deployment Results (*8*)

Deployment	Measure	Result
Charlotte, NC Opticom (Express Buses)	Bus Travel Time	4 minute decrease
	Cross Street Delays	Not unacceptable
Portland, OR TOTE & LoopComm Tests	Bus Travel Time	Reduction noted
Bremerton, WA	Bus Travel Time	10% decrease
	Stopped Delay/vehicle	Insignificant
Chicago, IL Cermak	Bus Travel Time	2-3 minute decrease from 13-17 minutes
MN Louisana Ave Opticom Hi-Priority	Bus Travel Time	38% decrease
	Auto Stopped Delay	23% increase
MN Louisiana Ave Opticom Med/Lo-Priority	Bus Travel Time	No change
	Auto Stopped Delay	No change
MD SHA Anne Arundel	Bus Travel Time	13-18% reduction
	Auto Travel Time – Same Direction	9% decrease
	Auto Travel Time – Opposing Direction	4-5% increase
Los Angeles, CA Metro Rapid (attributable component)*	Bus Travel Time	8-10% decrease
Seattle, WA Rainier*	Priority Bus Delay	34% decrease
	Bus Intersection Stops	24% decrease
	Bus Travel Time	8% decrease
Portland, OR Pilot Routes*	Bus Travel Time	10% decrease
	On Time Performance	8-10% improvement

* Works currently in progress (initial results)

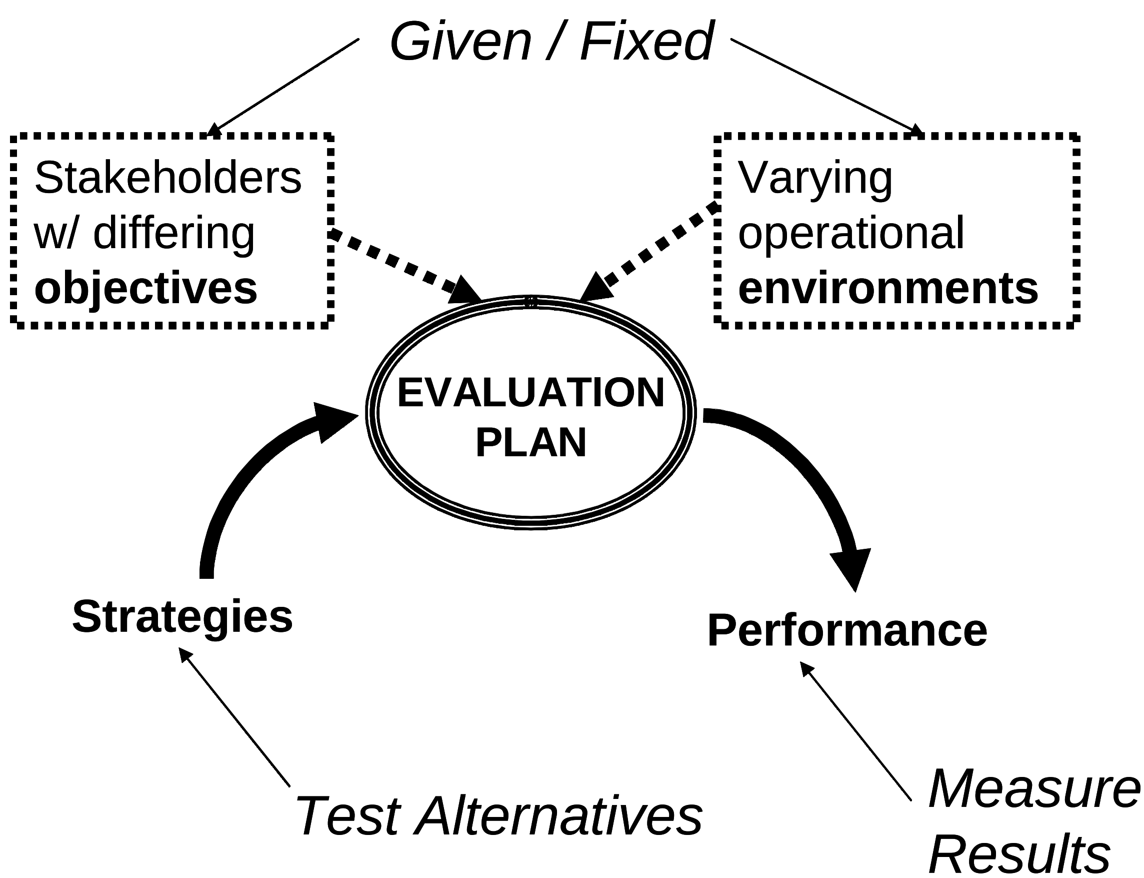

FIGURE 1 Framework Concept

TABLE 2 Evaluation Measures

Objective	Measure	Measurement
1.0 Bus Service Reliability (transit schedule adherence)	1.1 On Time Performance (OTP)	% of arrivals in on-time window at timepoint(s)
	1.2 Time Reliability	Standard deviation of elapsed time between timepoints or endpoints
	1.3 Perceived OTP	Survey measure of rider opinion
	1.4 Spacing	Maximum headway measured at timepoint(s)
	1.5 Arrival Reliability	Standard deviation of delta (actual time vs. scheduled) at timepoint(s)
2.0 Bus Efficiency (transit travel time savings)	2.1 Running Time (RT)	Elapsed time(mean) between start and end points
	2.2 95th-percentile RT	95th-percentile elapsed time between start and end points
	2.3 Trip Time	Weighted passenger time on board (in-vehicle)
	2.4 Perceived Travel Time	Survey of change in riders' opinions before & after
3.0 Other Traffic-Related Impacts	3.1 Overall Delay	Delay by [corridor or intersection], [person or vehicle]
	3.2 # of stops	Stops by [corridor or intersection], [person or vehicle]
	3.3 Mainline Travel Time	percentile or average operating speed
	3.4 Cross Street Delay	Maximum, 95th-percentile, or average delay
	3.5 Fuel Consumption and Emissions	Model output for corridor, average per vehicle
	3.6 Overall System Efficiency	Throughput achieved vehicles per hour, persons per hour
	3.7 Intersection Safety	Red light running, accident frequency

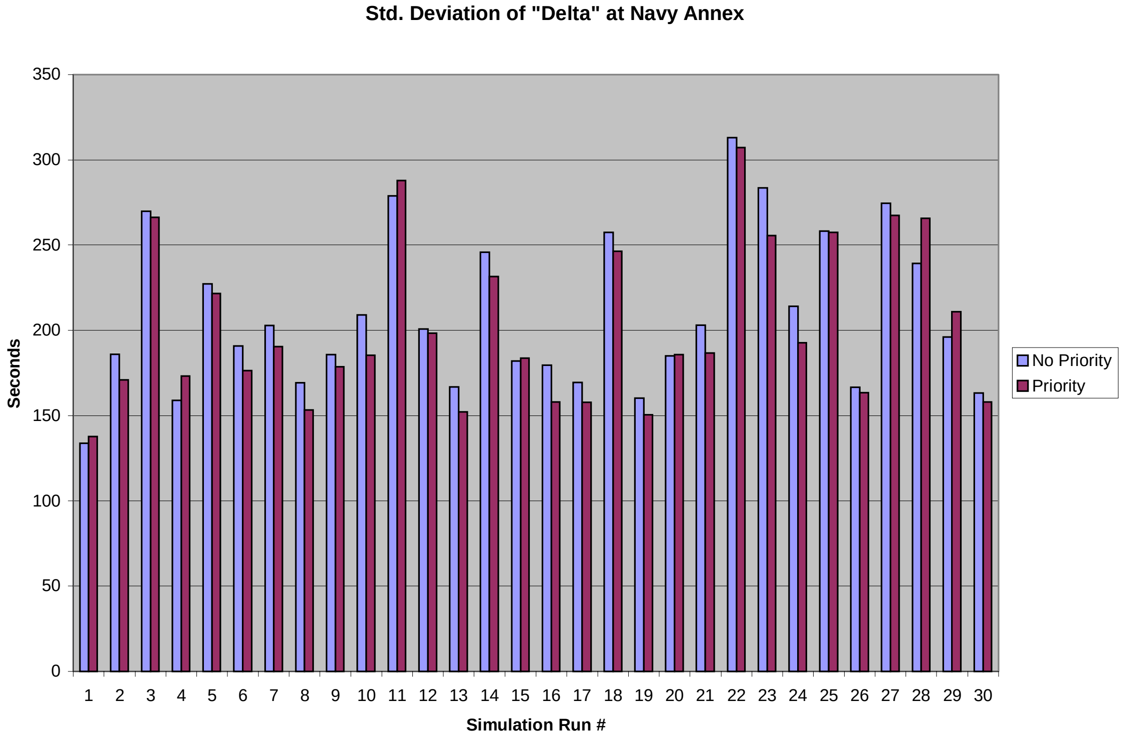

FIGURE 2 Standard Deviation of "Delta" Time at Navy Annex

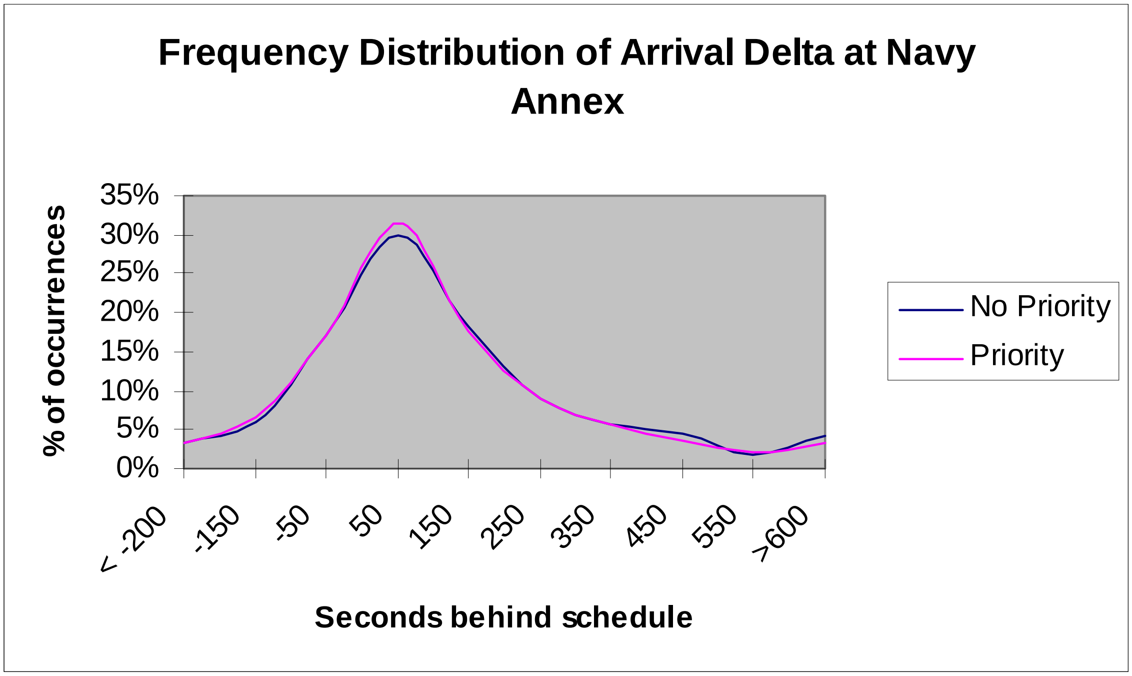

FIGURE 3 Alternative Visualization of Arrival Reliability

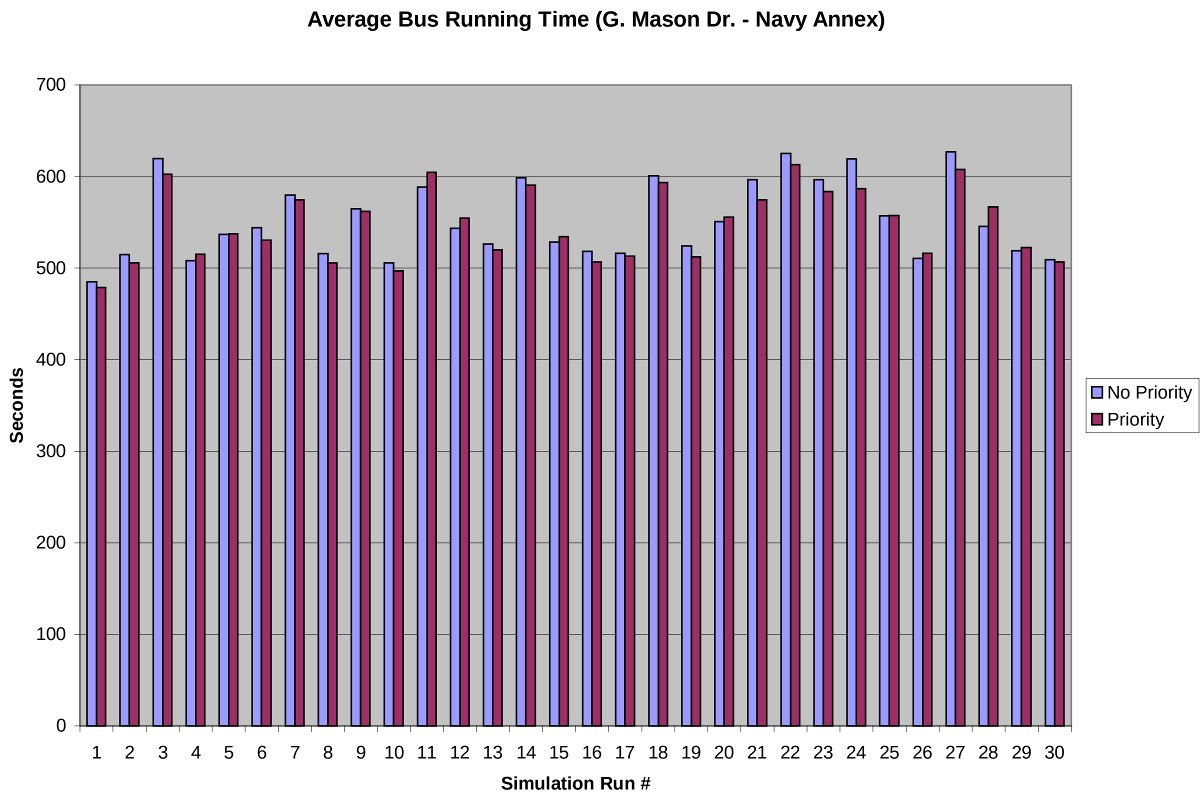

FIGURE 4 Average Bus Running Time

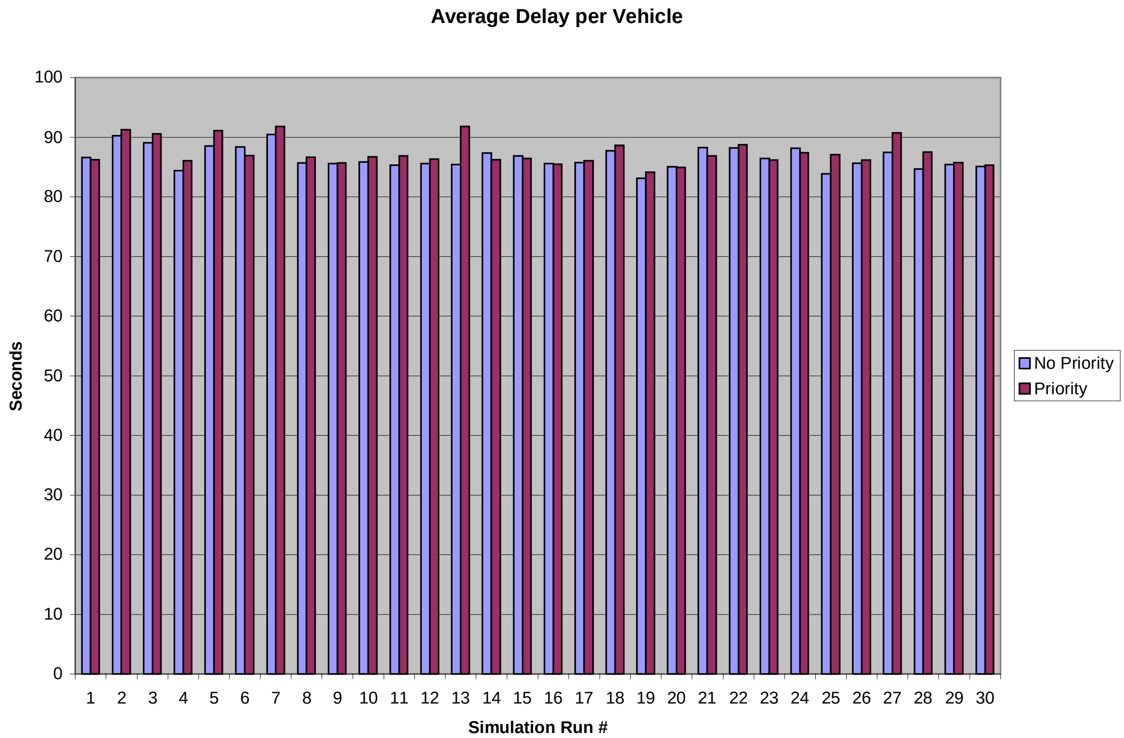

FIGURE 5 Average Vehicle Delay

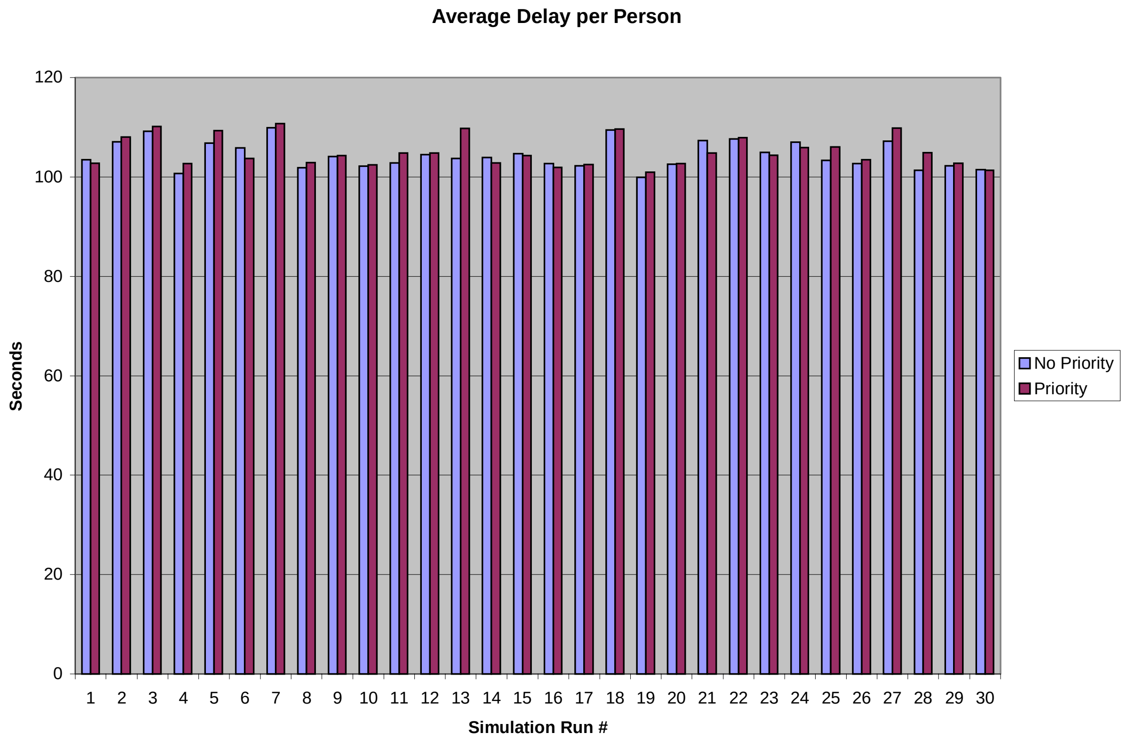

FIGURE 6 Average Person Delay