Methodology for Selecting the Most Promising Corridors for Active Transit Signal Priority Deployments

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ABSTRACT

Transit agencies are increasingly considering the deployment of transit signal priority systems along urban corridors. However, the number of parameters affecting the operation of such systems makes it difficult to estimate their expected benefits prior to deployment. To address this problem, simulation can be used, but the modeling efforts required make this approach non efficient for evaluating a large number of corridors. This paper presents a methodology that has been developed for evaluating the potential impacts of priority system deployments along urban arterials without using simulation. The methodology estimates the potential benefits of proposed deployments through consideration of parameters characterizing key roadway geometry, traffic flow conditions, traffic signal operations and transit service elements. These benefits are estimated by first considering the ability of each intersection to provide preferential treatments to approaching buses without causing significant negative impacts on the general traffic. A corridor-level evaluation is then produced by aggregating the evaluations of individual intersections. An evaluation of the methodology is presented by comparing its deployment recommendations with simulated hypothetical priority system deployments along a 39-intersection section of an urban arterial in Montreal, Canada.

INTRODUCTION

Faced with increasing bus travel times due to growing traffic congestion, many transit agencies are considering deploying preferential measures for buses at signalized intersections. The most common measures are temporary signal timing alterations, such as green extensions and early green recalls. Green extensions are typically offered to avoid stopping buses projected to arrive a few seconds after the end of the green, while early recalls shorten the wait of buses that have been stopped by a red signal. While such measures have historically been primarily considered for reducing travel times, new application objectives have emerged from the ability to track vehicle movements and retrieve on-line information about individual vehicles and traffic flow conditions. As examples, priority measures can now selectively be granted to help only buses that are behind schedule, to maintain certain regularity between successive arrivals, or when specific traffic conditions are met.

Despite potential transit benefits, there also exists a potential for negative traffic impacts, mostly through the temporary green time reductions that are imposed on certain traffic movements to accommodate buses traveling within other movements. On arterials, another fear is that priority may disrupt traffic patterns and lead to an effective loss of signal coordination. However, numerous studies have demonstrated the possibility of providing priority along coordinated arterials without significantly disrupting traffic progression patterns if the treatments are designed while considering the needs of both buses and general traffic [*1*].

Because of their potential impacts on traffic, signal priority systems should not be deployed without prior assessment. Due to the large number of impacting parameters, it is generally recommended that potential gains and impacts associated with projected deployments be evaluated through simulation. While such an approach is well-suited for systems targeting isolated intersections or a single arterial, it is problematic when considering multiple deployment sites. Such a problem was recently faced by the *Agence métropolitaine de transport* (AMT) in Montréal, Canada, which wished to select two or three deployment corridors among a set of 20 heterogeneous candidates. The shortest deployment site had one intersection, while the longest extended over 39. The problem was linked to the efforts required to develop calibrated simulation models adequately representing traffic conditions along each corridor. In this case, not enough resources were available to develop suitable models for all 39 corridors.

This paper addresses the issue of how to determine the best deployment corridors among a group of candidates when limited resources are available. This problem is addressed by presenting an evaluation methodology that evaluates the potential impacts of projected signal priority systems without requiring simulation. This methodology is designed to provide summary estimates within the context of preliminary deployment evaluations and does not therefore attempt to produce exact predictions of expected benefits. A typical application would for instance be to identify promising corridors for which additional analysis, such as simulation studies, should be conducted.

EVALUATION OF EXISTING METHODOLOGIES

Prior to this work, only one non-simulation methodology allowed the evaluation of potential benefits associated with projected transit signal priority system deployments [*2*]. This methodology is part of the *Screening for ITS* (SCRITS) spreadsheet analysis tool. It produces a benefit-cost ratio that can be used to rank various projected deployments or determining whether they are worth pursuing.

A major problem associated with this methodology is the nature of some required input parameters. For instance, the methodology requires an estimate of the percentage of bus travel time that is attributable to traffic signal delays, the proportion of this delay that could be reduced if a priority system is deployed, and the delay that would be imposed on cross-street traffic. The main problem with these data is that they can often only be obtained through simulation or detailed traffic flow analyses.

Recognizing the above problem, Chada and Newland [*1*] developed a filtering tool to determine whether the SCRITS methodology should be used. This tool assesses the potential of an intersection or corridor to benefit from a priority system based on seven conditions: presence of express transit service during peak traffic period, presence of express service off-peak, volume-to-capacity (v/c) ratio above 1.00 on cross-streets, high flow along the corridor, simultaneous bus arrivals at an intersection, and bus tracking system availability. Existence of at least three conditions leads to a deployment recommendation and a justification of using SCRITS to determine the cost-benefit ratio of the proposed system.

The above filtering tool, however, does not completely eliminate the need for detailed analysis or simulations to provide the input demanded by SCRITS. The methodology presented in this paper solves this problem by allowing summary evaluations of proposed signal priority deployments to be performed without simulations. Evaluations are based on a number of key input parameters describing the roadway geometry, traffic flow conditions, signal operation, and transit service along the corridor under investigation. Contrary to SCRITS, the goal is not to produce a benefit-cost ratio but to simply return an evaluation score for ranking proposed deployments and determining which one are worth pursuing. It was determined that reliable cost-benefit ratios would be difficult to produce given the uncertainty with the benefits that can be obtained by priority systems and the dependency of deployment costs on the traffic control and detection equipment already in place.

EVALUATION PARAMETERS

An operational system analysis and review of past simulation studies and field deployments [see for instance *3*-*9*] was first conducted to determine the parameters affecting transit signal priority systems. As shown in Figure 1, this lead to the determination of parameters related to transit operations, traffic flow conditions, roadway geometry, and traffic signal control. Below is a general rationale for the various parameters shown in the figure:

- **Number of priority requests.** The efficiency and justification of priority system implementations depend on their utilization level. On one hand, a system receiving very few priority requests may not justify its deployment and operating costs. On the other hand, frequent requests may reduce system efficiency by constraining the ability to accommodate all buses or lead to significant delay increases on cross-streets due to frequent signal timing alterations.

- **Prediction of intersection bus arrival times.** The efficiency with which a system can respond to priority requests depends on the ability to accurately predict vehicle arrivals at intersections. A bus arriving later than expected may for instance miss a granted green extension, thus resulting in unnecessary signal timing alterations and traffic disruptions. Here, prediction accuracy depends not only on the level of interference generated by the surrounding traffic, but also on the variability of service times at bus stops.

- **Ability to respond to priority requests.** Response to priority requests depends on the ability to move green time around. This is determined by the minimum green specified for each phase, the number of phases in a cycle, the maximum allowed green extension to accommodate buses, the need to maintain coordination with adjacent intersections, and the need to avoid intersection blockage by downstream queue spillbacks in periods of congestion. Utilization of compensation measures to reduce traffic impacts may create further operational constraints.

- **Traffic impacts.** Increased stops and delays are typically imposed on traffic movements served by phases that are shortened by priority requests. However, traffic along bus routes may also benefit from delay reductions due to elongations of green signals.

- **Evaluation of benefits.** Determining overall benefits require comparing gains achieved by transit vehicles against induced negative traffic impacts. Such a comparison requires considering elements such as vehicle occupancies, proportion of traffic served by prioritized and penalized phases, and congestion level on traffic movements.

PARAMETER PRIORITIZATION

The identification of impacting parameters was followed by a categorization into primary, secondary and tertiary parameters based on their relative impacts on system operation. Many parameters were also modified to express them in a form more suitable for the evaluation methodology.

Primary Parameters

Primary parameters are defined as those having a direct impact on the capacity of a system to provide appropriate timing alterations and which must therefore be known for correctly assessing potential system benefits. These include:

- Frequency of priority requests,
- Green time maximum extension,
- Proportion of green time available for reallocation, and
- Congestion level on penalized movements.

The frequency of priority requests must remain within practical lower and upper limits to ensure effectiveness of operation. In this case, it is important to distinguish between frequency of priority requests and frequency of bus arrivals. Since not all buses may request signal timing alterations, a system operating at an intersection with a high frequency of buses may for instance not be justified if most buses normally arrive during the green.

System efficiency further depends on the ability to make appropriate timing alterations. This is linked not only to the maximum allowed green signal extension, but also to the availability of spare green time that can be moved around. As indicated in Equation 1, this is primarily function of the proportion of a signal cycle that is consumed by unmovable intervals, such as minimum green, amber, all-red and pedestrian clearance intervals.

$$P_{g\ disp} = \frac{C - \sum_{i=1}^{N}\left(g_{min\ i} + j_{pi} + j_i + r_i\right) - f_k\left(g_k - g_{min\ k}\right)}{C} \qquad [1]$$

where : $p_{g\ disp}$ = Proportion of available green time in cycle,
C = Cycle length (s),
N = Number of phases in cycle,
$g_{min\ i}$ = Minimum green for phase *i* (s),
g_k = Normal green for prioritized phase *k* (s),
$g_{min\ k}$ = Minimum green for prioritized phase *k* (s),
j_{pi} = Pedestrian clearance for phase *i* (s),
j_i = Amber duration for phase *i* (s),
r_i = All-red duration for phase *i* (s),
f_k = 1 for green extensions and early green recalls, 0 for phase insertion.

In Equation 1, $f_k \cdot (g_k - g_{min\ k})$ indicates that the green time beyond the minimum green for the prioritized phase *k* should not be considered as available green time for actions extending this phase (f_k=1), but should be so for treatments targeting other phases (f_k=0). A proportion per cycle rather than an actual green duration is further used to consider that, for instance, 10 seconds of available green within a 60-second cycle would not provide the same priority opportunities as 10 seconds within a 120-second cycle. Finally, an element not considered is constraints in moving the green time around imposed by the use of compensation measures to allow penalized traffic to recover from signal alterations, such as request denials for *n* cycles following a priority action.

The congestion level on penalized traffic movements is used to quantify incurred delays. A penalized movement is any one with a green interval temporary shortened. While the preference was to avoid using v/c ratios as an evaluation parameter, numerous studies indicated a strong link between v/c ratio and system performance, mainly in the form of increases in potential negative traffic impacts with priority systems affecting traffic movements with high v/c ratios. To avoid forcing field data collection, two choices are offered for quantifying the level of congestion of penalized movements. If sufficient data exists, the calculated v/c ratio can be inputted. In other cases, Table 1 may be used to determine an approximate ratio reflecting observed traffic conditions. If only one phase is penalized, the ratio corresponding to the traffic movement with the highest flow rate would typically be entered. However, a weighted ratio reflecting the flows associated with the various penalized movements may also be entered. For more than one penalized phase, a ratio characterizing the average traffic conditions on the various penalized movements should instead be provided.

Secondary Parameters

Secondary parameters are those having a certain impact on system performance and for which knowledge is recommended but not required. As detailed below, this category includes parameters characterizing traffic signal operation, general traffic conditions and transit service along priority corridors:

- Congestion level on prioritized movement,
- Ratio of traffic flows benefiting from priority over penalized traffic flows,
- Location of bus stops relative to intersection,
- Bus detection interval prior to intersection arrival,
- Bus progression interferences on intersection approaches,
- Use of exclusive bus lanes,
- Duration of red interval on prioritized movements,
- Traffic signal coordination along prioritized corridor,
- Traffic signal coordination on penalized cross-streets,
- Timing plans with multiple phases,
- Protected left turns on penalized traffic movements,
- Intersection blockage by downstream queue spillback, and
- Frequency of conflicting priority requests.

The congestion level for traffic movements served by prioritized phases considers not only the potential for buses traveling within these movements to be delayed by heavy traffic or queued vehicles, but also the potential delay reductions for the general traffic following the provision of longer green intervals. While the v/c ratio is again used as a quantification parameter, only approximate values are required here. Values characterizing the general traffic conditions on the prioritized approach can again be taken from Table 1. If traffic in more than one direction is benefiting from the signal timing alterations, a ratio characterizing the traffic conditions on the approach on which the prioritized buses are traveling should then be used to allow adequate considerations of traffic interferences on bus progression.

The ratio of penalized traffic flows to flows benefiting from the priority system determines the capacity to use delay reductions on certain traffic movements to compensate for delay increases on other. In most cases, this ratio can be derived by summing the flows serviced by phases benefiting from added green time and dividing this sum by the flows serviced by shortened phases. Given the preliminary nature of the evaluations, only an approximate ratio again is required here.

A number of parameters further account for the ability to correctly predict vehicle arrival times at intersections. These include the location of bus stops relative to the intersection, as nearside stops require consideration of bus dwell times, how far ahead a bus is detected prior to its arrival, as more advanced detection typically leads to increased uncertainties, delays imposed on bus progression due to their interactions with other traffic, and whether a bus is traveling on an exclusive lane.

Five additional parameters characterize traffic signal operations. The red duration on the priority approach first considers the increased potential for bus delay reductions associated with longer red intervals. Two other parameters account for the disruptions that timing alterations might have on signal coordination and traffic patterns along the prioritized corridor and cross-streets. The number of phases in a timing plan further accounts for operational constraints imposed by complex phasing sequences, such as the inability to respond to an approach bus due to the inability to draw green time from a following phase and the inability to move available spare green within other phases time beyond their immediately adjacent phases. The protected left turn parameter finally accounts for the increased traffic delays that may result from a reduction in the duration of a protected left-turn signal, as some vehicles may then have to wait for an available gap or wait for the next cycle to cross the intersection.

The queue blockage parameter assesses the disruptions to bus progression caused by congestion downstream of an intersection and the potential that these disruptions may prevent buses from benefiting from granted timing alterations. The frequency of conflicting requests finally takes into account the proportion of requests that may not be granted due to conflicts with other buses.

Tertiary Parameters

Tertiary parameters are those having relatively minor impacts and for which knowledge is useful but not required. These include:

- Variability of bus dwell times at bus stops,
- Bus occupancy rate,
- Utilization of countdown signals for pedestrians, and
- Number of traffic lanes on intersection exit links.

The variability of bus dwell primarily impacts the ability to predict bus arrivals at an intersection. The bus occupancy is further useful when attempting to rationalize the deployment of a priority system on a person- basis rather than a vehicle basis. Often, however, priority systems are specifically deployed to promote transit ridership. In such cases, the occupancy of buses may thus not be viewed as a relevant parameter. The number of traffic lanes on the intersection exit assesses the safety problems associated with vehicles changing lanes within an intersection to go around a stopped bus, as such behaviour may not be favourably viewed by some traffic agencies. The parameter considering pedestrian countdown signals finally considers the added difficulties of shortening signal phases that are imposed by these signals.

EVALUATION METHODOLOGY

Two steps are used to determine the impacts of priority systems on urban arterials. The first evaluates the impacts at individual intersections, while the second converts these impacts into a corridor-level assessment.

Intersection-level evaluation

The evaluation of impacts on individual intersections is based on the model defined by Equation 2. This model first defines a base evaluation score of 100, representing a situation for which it would be advantageous to deploy a priority system. Adjustment factors are then applied to this base score to account for the impacts of various parameters. Factors below 1.00 will represent a negative impact on the potential to successfully provide priority without significantly impacting traffic, while factors greater than 1.00 will represent positive impacts and factors of 1.00 the absence of significant impacts or parameters without input value.

$$s_c = 100 \cdot f_1 \cdot f_2 \cdot f_3 \ldots f_{k-1} \cdot f_k \qquad [2]$$

where: s_c = Intersection-level score,
f_i = Adjustment factor for parameter i,
k = Number of parameters considered.

Following application of Equation 2, scores greater than 100 will indicate intersections for which excellent conditions exist for transit signal priority deployment while scores lower than 100 will indicate conditions that may create difficulties in responding to priority requests or intersections where negative traffic impacts may outweigh potential transit benefits.

It should be noted here that the evaluation methodology is currently designed for the evaluation of priority systems considering to buses traveling in one direction only. This is consistent with a majority of system deployments, where it is typically desired to improve transit service in a specific direction. The methodology must therefore be viewed as a first step in the development of a more general methodology. The evaluation of bi-directional systems or systems providing priority to buses on crossing paths would be possible through the addition of new factors or changes in values assigned to existing factors.

Corridor-level evaluation

For the evaluation of priority corridors, a methodology similar to Equation 2 was first suggested but determined to be not ideal. Since corridors of different lengths may be evaluated, the methodology should produce evaluations on a common reference platform to facilitate comparisons. For instance, consider a corridor covering 5 intersections and another one covering 10. Further assume that scores of 90 have been obtained for each intersection within each corridor. While the two corridors theoretically offer the same potential benefits at each intersections, multiplying together the score of each intersection would produce a much greater aggregate score for the 10-intersection corridor (90^{10}) than for the 5-intersection one (90^{5}). The approach that has been adopted consists instead in a simple averaging of the scores produced for each intersection in a corridor, as expressed by Equation 3. For the above example, this would correctly return equal evaluations of 90 for both corridors.

$$S = \frac{\sum_{i=1}^{n} s_{c\,i}}{n} \qquad [3]$$

where: S = Corridor-level score,
s_{ci} = Score for intersection i,
n = Number of intersections in corridor.

ADJUSTMENT FACTORS

Table 3 presents the adjustment factors that have been assigned to each parameter to reflect their relative impacts on bus delays, the general traffic, the capacity of a system to respond to priority requests and the ability of prioritized buses to benefit from the granted signal alterations. Depending on the parameter considered, these factors are either function of a single input parameter or a combination of related parameters. To reflect the relative anticipated impacts associated with each category of parameters, the factors for primary parameters have no predefined minimum or maximum values, while the secondary parameters factors are generally assigned values between 0.80 and 1.20, and the tertiary parameters factors values between 0.90 and 1.10.

The last column of Table 3 indicates whether the factors were determined from information found in the literature, theoretical analyses and/or simulation analyses. To support the development of the methodology, various theoretical signal priority scenarios were simulated with version 2.30 of the INTEGRATION microscopic traffic simulation software [*10*]. The objective of these simulations was to assess system effectiveness in a variety of traffic and traffic signal operating conditions. Evaluations were conducted within the model's priority logic modeling constraints, which restricted the provision priority to minimize bus delay, assume bus detection 100 meters upstream of signalized intersections, forbid any changes in signal cycle length, and require green extension or early recalls to be made at the expense of the immediately adjacent phases. These simulations considered both a four-legged intersection with various main and cross-street geometries and a coordinated arterial with 10 equally-spaced intersections. The single-intersection scenario was used to study the impacts of individual parameters on priority system operation, while the arterial scenario was used to study impacts on traffic signal coordination and traffic progression patterns.

Table 3 further indicates two factors for considering the congestion level of penalized traffic movements. The first factor ($P04_a$) considers the observed congestion level, while the second ($P04_b$) is introduced to compensate for the inability of the v/c ratio to consider impacts associated with the use of alternative signal timing and phasing plans. For instance, consider two intersections with a 600 veh/h penalized flow. Further consider that the first intersection has a 120-second cycle normally offering 60 seconds of green to the penalized movement, and that the second operates with a 90-second cycle offering 45 seconds of green. In the absence of priority, a v/c ratio of 0.63 characterizes penalized movements at both intersections. However, a 10-second green time reduction would impact more significantly traffic flow conditions at the intersection with the 90-second cycle than at the one with the 120-second cycle. In the former case, the green time reduction would temporarily increase the v/c ratio to 0.81, while it would only increase to 0.75 in the later.

To consider the impacts of signal settings, a sensibility test has been introduced to determine an adjusted v/c ratio for penalized traffic movements. This test recalculates the v/c ratio using Equation 4 under the hypothesis of an arbitrary 10-second reduction of the green signal serving the penalized movements. This produces an estimate of the temporary v/c ratio that exists when signal timing are altered to accommodate buses. This effective ratio is then used in Table 2 to determine values for the adjustment factor $P04_b$. While the choice of a 10-second green reduction is based on maximum green signal extension limits often used in practice, smaller reductions will however be considered when the maximum allowed extension or the calculated available green time is less than 10 seconds.

$$\left(\frac{v}{c}\right)_{\text{effective}} = \frac{\left(\frac{v}{c}\right) \cdot g_{tp}}{g_{tp} - \min\left[10, e_{\max}, \left(P_{g\ disp} \cdot C\right)\right]} \qquad [4]$$

where: $(v/c)_{effective}$ = Effective v/c ratio,
(v/c) = v/c ratio under normal signal operation,
C = Cycle length (s),
g_{tp} = Normal green interval of phase usually shortened by priority (s),
e_{max} = Maximum allowed green extension (s),
$P_{g\ disp}$ = Proportion of green time within cycle available for reallocation.

Given the complexity of interactions between the evaluation parameters, the adjustment factors of Table 3 can only be considered as estimates of the true impacts associated with each parameter. An element particularly difficult to model is how various parameter combinations may impact the overall operation of priority systems. While each parameter may produce specific impacts, the overall impacts from a combination of parameters may not always correspond to the summation of individual impacts. Furthermore, while these combined effects can be evaluated through simulation, the multitude of possible combinations makes it virtually impossible to determine adjustment factors for each possible grouping. Simulation study results will also be function of the simulation modeling assumptions, which never perfectly replicate driver behaviour. The factors of Table 3 must therefore be considered as being subject to refinement as a better understanding of the impacts associated with each parameter, and of the relations among parameters, is developed.

DEPLOYMENT RECOMMENDATIONS

The following deployment recommendations were established based on the evaluation scores returned by the methodology:

- $0 \leq$ Score < 50: Not recommended due to lack of potential benefits
- $50 \leq$ Score < 100: Somewhat recommended, with adjustments for problematic intersections
- $100 \leq$ Score < 150: Recommended
- Score ≥ 150: Strongly recommended

To avoid situations in which a deployment recommendation may be prevented by a weak evaluation at a few intersections, it is suggested to consider both the corridor-level score obtained by averaging individual intersection scores and the average score produced by removing the one or two intersections with the lowest scores. A significant difference between the two averages would indicate that only a single or a few intersections may be problematic. This may lead more particularly to the identification of intersections where priority should not be provided or special operational constraints be considered.

DESIGN RECOMMENDATIONS

At the end of each analysis, corrective actions are suggested for any factor returning a value of less than 0.90 to assist in improving system performance. An example would be a recommendation to reduce the maximum green extension allowed if congestion on cross-street is a problem. Recommendations against system deployment are also considered for factors returning a value of less than 0.50.

The input parameters are also used to provide suggestions as to the type of priority strategy to promote. For instance, a high bus frequency may suggest a strategy centered on uniformity in inter-vehicle arrival times, or the existence of significant variability in bus travel times a strategy centered on schedule adherence. However, the methodology should not be seen as a tool determining the ideal type of strategy to implement, as this decision depends on the objective behind the proposed system deployment and is often heavily influenced by political or institutional decisions.

EVALUATION OF METHODOLOGY

Evaluation of the methodology can conducted by comparing the deployment scores it produces against the results of simulated priority system deployments within the INTEGRATION microscopic model for a real-world corridor. For this evaluation, comparisons were made for projected priority system deployments along a 9-kilometer section of Pie-IX Boulevard in Montreal, Canada, extending from Hochelaga Street to the south to Henri-Bourassa Boulevard to the north. This section of Pie-IX Boulevard features 3 lanes of traffic per direction and 39 signalized intersections with an array of minor and major *cross-streets.* The evaluation focused more precisely on the AM peak period when traffic is predominantly flowing south. Depending on the intersection, southbound flow rates vary between 1100 and 2500 veh/h, with cross-street rates varying between 500 and 1300 veh/h. For this period, traffic signals at various clusters of intersections are controlled by a fixed-time system imposing cycles between 70 and 130 seconds.

As shown in Figure 3, two bus lines service the arterial during the morning peak. The first provides a southbound express service with 11 stops and buses every 3-4 minutes. The second provides a regular north-south service with stops at most intersections and buses every 5 minutes. For the evaluation, two transit service configurations are considered. The first features express buses traveling on an exclusive lane running contraflow to the northbound traffic with regular buses offering traditional curb lane service. The second has all buses traveling on the southbound curb lane. Three priority strategies each providing 10 seconds of maximum green signal elongation for buses traveling southbound are further considered, leading to a total of six evaluation scenarios. The first strategy offers priority only to express buses, the second only to regular buses, while the third considers all southbound buses. Priority for buses traveling north is not considered as these have typically much lower ridership than southbound buses.

Figures 5, 6 and 7 present the intersection-level and corridor-level evaluation results for the various scenarios considered. Evaluations were conducted for a one-hour evaluation period starting after a 15-min initialization period. To account for the stochastic nature of the INTEGRATION simulation model, 30 repetitions with different random number seeds were conducted for each scenario.

The evaluation results first indicate that intersection scores are generally coherent with the simulation results. It is observed that scores above 100 are typically obtained for intersections where priority provides bus delay reductions without significant traffic impacts. While traffic movements at some intersections experience significant delay increases, these increases tend to be compensated by delay reductions for other movements. This is evidence by the points along the dotted line, which indicate for most intersections a reduction or no significant impact in overall traffic delays (please note the reverse scale). It is also observed that intersections with notable negative traffic impacts are typically assigned scores lower than 100. This is for instance the case for the intersections with Bellechasse and Jean-Talon, Streets, two busy cross-streets, where the delay reductions for buses and arterial traffic cannot compensate the delay increases for cross-street traffic.

The low scores returned by the methodology for Sherbrooke Street and Industriel Boulevard are also due to high cross-street traffic. However, the simulations do not indicate significant traffic impacts. This is due to simulation effects. For Industrial Boulevard, southbound Pie-IX traffic is served by a leading green phase that is followed by a general green. Since buses tend to arrive during the leading green, the INTEGRATION priority logic then typically implements a green extension on the leading green phase at the expense of following general green. This results in no overall change in available green time for the cross-street traffic. For Sherbrooke Street, the phase serving the prioritized buses is the last of the cycle. While a majority of buses request a green signal extension, no priority is offered here as the provision of green extensions would violate the model's constant signal cycle constraint.

The absence of low evaluation scores for many intersections with increases in bus delay can again be explained by simulation effects. These negative impacts are primarily due to a change in the moment at which buses typically arrive at the intersections. While buses may have regularly arrived during a green interval under the existing signal control scheme, the provision of signal priority at upstream intersections may change this pattern and cause buses to arrive more frequently during a red interval. Thus, even though early greens may be deployed to reduce the delay incurred by the buses being stopped, the remaining delays may still remain higher than those experienced before the priority system deployment.

The delay reductions observed at the northern end of the corridor (right-hand side of diagrams) are due to effects indirectly attributable to the priority measures but difficult to quantify outside a simulation environment. At this end, traffic conditions are relatively congested due to queues generated at the intersection with Fleury Street. These queues frequently spill across upstream intersections, thus causing waste green time and temporary capacity reductions. In this context, green signal extensions and early green recalls create temporary capacity increases that contribute to delay the onset of congestion and reduce the overall delays incurred by the traffic.

At the corridor level, the evaluation scores ranging between 81 and 148 translate into deployment recommendations of varying strength for all scenarios considered. These recommendations are supported by indications that the prioritized buses would benefit from the priority system in each scenario while the general traffic would not unduly suffer. It can particularly be observed that scenarios with scores above 100 are those producing the smaller overall negative impacts on cross-street traffic, while those with scores below 100 have the highest impacts. The fact that the scenario with the highest score is not the one with the lowest overall delays is further explained by considering that the methodology not only consider impacts on delays, but also the capacity to grant priority requests and the ability of buses to benefit from the signal timing alterations. Consequently, while two scenarios may produce similar delay impacts, different evaluation scores may result if one system is assessed to provide greater capability to accommodate buses.

From a general standpoint, the following observations can be made from the evaluation results:

- As expected, offering priority only to express buses traveling on an exclusive lane produces the best corridor and intersection evaluation scores, with scores of less than 100 attributed to only a handful of intersections.
- Offering priority to express buses traveling on the curb lane typically produces lower evaluation scores than the scenarios placing the buses on an exclusive lane. These results reflect the increased potential for interferences to bus progression by the general traffic, particularly at the congested northern end of the corridor.

- Offering priority only to regular buses produces evaluation scores that are further lower. This is explained by an increased in the frequency of prioritized buses from 12 to 17 buses per hour, which produces more frequent timing alterations and greater traffic impacts.
- The lowest evaluation scores are produced when offering priority to all southbound buses. These low scores are attributed to the resulting high frequency of priority requests. As the number of requests reaches 29 per hour, this translates into a need to implement signal timing alterations every 2 minutes and a risk of traffic signal coordination loss.

Divergences between the simulation and analytic results can be explained by a number of modeling elements. First, while it is difficult for the methodology to consider the full complexity of interactions between the various parameters, this complexity is implicitly considered in the simulations. The simulation results are further function of the implicit modeling assumptions within the INTEGRATION model and how well these assumptions replicate reality. Finally, the methodology is not designed to consider situations in which a high proportion of buses normally arrive during a regularly scheduled green interval and do not require preferential treatment. Such a situation may produce high evaluation scores but relatively small traffic impacts or changes in bus performance measures.

CONCLUSIONS

This paper presented a methodology for evaluating the impacts associated with proposed transit signal priority system deployments based on a number of key parameters characterizing roadway geometry, traffic signal control operation, traffic flow conditions and transit service elements at each intersection. This methodology has been developed for preliminary deployment studies, where the focus is on the identification of promising deployment sites and where there may not be enough resources to conduct detailed simulation evaluations of each potential site. Its goal is not to produce exact estimates of potential impacts but to produce estimates that are accurate enough for the categorization of sites and the selecting of candidates warranting deployment or further studies.

While the evaluations indicate a general agreement between the deployment recommendations and simulated impacts for the scenario considered, additional scenarios considering a wider range of potential situations should be considered. Ideally, the methodology should be evaluated against the performance of real-world priority systems. Further research is also required to refine and validate the adjustment factors attributed to each impacting parameter, and more particularly, to quantify the combined impacts of groups of parameters. Corridor-level adjustment factors may also be developed to better capture the cumulative impacts of providing priority at successive intersections. Adjustment factors may further be developed to account for alternative priority strategies behind proposed deployments, such as strategies focusing on scheduled adherence or regularity of inter-arrival time instead of simple travel time minimization. Such factors may allow as well the consideration of strategic deployment decisions, such as deployments intentionally disregarding traffic impacts in an effort to create incentives for increased transit ridership. There is finally a need to expand the applicability of the methodology to system offering priority to buses traveling opposing in directions along a given corridor, or systems considering priority for buses traveling on crossing paths.

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Table 1 – Approximate volume-to-capacity ratios in absence of calculated ratios

Congestion level	v/c ratio range	Representative v/c ratio
Very low	0,00 – 0,25	0,125
Low	0,25 – 0,50	0,375
Moderate	0,50 – 0,80	0,650
Congested	0,80 – 0,90	0,850
Near-saturated	0,90 – 0,95	0,925
Saturated	> 0,95	1,000

Table 2 – Adjustment factors

Type	ID	Parameter	Value	Factor	Validation
Primary	P01	Frequency of priority requests (nr)	0 – 10 requests/hour	1.00	Literature Simulations
			11 – 20 requests/hour	1-0.025(10-nr)	
			> 20 requests/hour	0.75	
	P02	Green time maximum extension	0 – 5 s	1.00	Theoretical considerations
			6 – 10 s	1.05	
			> 10 s	1.10	
	P03	Proportion of green time available for reallocation	< 2 s (absolute time)	0.00	Theoretical considerations
			0 - 5% of cycle	0.90	
			5 - 10% of cycle	1.00	
			10 - 15% of cycle	1.10	
			> 15% of cycle	1.20	
	P04$_a$	Congestion level on penalized movements	No penalized movement	1.20	Literature, Simulations
			0.00 – 0.25	1.2 – 0.40 v/c	
			0.25 – 0.80	1.1 – 0.73 (v/c – 0.25)	
			0.80 – 0.90	0.7 – 2.0 (v/c-0.80)	
			0.90 – 0.95	0.5 – 10.0 (v/c-0.90)	
			> 0.95	0.00	
	P04$_b$	Effective congestion level on penalized movements	No penalized movement	1.00	Simulations
			v/c ratio penalized movements: 0.00 – 0.24	1.00	
			0.25 – 0.49	1.00	
			0.50 – 0.79	0.80	
			0.80 – 0.89	0.60	
			0.90 – 0.94	0.25	
			≥ 0.95	0.00	
Secondary	S01	Congestion level on prioritized movement	v/c ratio : 0.00 – 0.24	1.00	Literature Simulations
			0.25 – 0.49	1.05	
			0.50 – 0.79	1.10	
			0.80 – 0.89	1.15	
			0.90 – 0.94	1.05	
			≥ 0.95	0.90	
	S02	Ratio of traffic flows benefiting from priority over penalized traffic flows	Ratio < 1	0.80	Theoretical considerations
			Ratio = 1 – 5	0.90	
			Ratio = 5 – 10	1.00	
			Ratio = 10 – 20	1.10	
			Ratio = > 20	1.20	
			No penalized movement	1.20	
	S03	Location of bus stops relative to signalized intersections	None	1.10	Literature Simulations
			Farside	1.00	
			Nearside	0.90	
			Farside and nearside	0.90	
	S04	Bus detection interval prior to arrival at intersection	0 – 5 s	0.80	Literature
			5 – 10 s	0.90	
			11 – 20 s	1.00	
			> 20 s	0.95	
	S05	Bus progression interferences on intersection approaches	Exclusive bus lane	1.00	Theoretical considerations
			No exclusive bus lane		
			→ Minor Interferences	1.00	
			→ Moderate interferences	0.90	
			→ Major interferences	0.80	
	S06	Use of exclusive bus lanes	No	1.00	Literature Simulations
			Yes	1.20	
	S07	Duration of red interval on prioritized movements	0 - 15 s	1.00	Theoretical considerations
			15 – 25 s	1.10	
			26 – 35 s	1.15	
			> 35 s	1.20	
	S08	Coordination along prioritized corridor	No	1.00	Literature
			Yes	0.95	
	S09	Coordination on penalized cross-streets	No	1.00	Literature
			Yes	0.80	

Table 2 – Adjustment factors (cont'd)

Type	ID	Parameter	Value	Factor	Validation
	S10	Timing plans with multiple phases	Plans with 2 phases Plans with 3 phases Plans with 4 phases Plans with more than 4 phases	1,00 0,90 0,85 0,80	Literature
	S11	Protected left turns on penalized traffic movements	No penalized movement Penalized movements : → Protected left turns → Permitted left turns : - P04$_a$=0,50–0,79 - P04$_a$=0,80–0,89 - P04$_a$=0,90–0,94 - P04$_a$ ≥ 0,95	1,00 1,00 0,95 0,90 0,85 0,80	Simulations and theoretical considerations
	S12	Intersection blockage by downstream queue spillback	No Yes → Exclusive bus lane? - Yes - No → S01 = 0,00–0,24 - No → S01 = 0,25–0,49 - No → S01 = 0,50–0,79 - No → S01 = 0,80–0,94 - No → S01 ≥ 0,95	1,00 1,00 1,00 0,90 0,85 0,80 0,90	Simulations
	S13	Frequency of conflicting priority requests	None (0 requests/hour) Low (1 – 4 request/hour) Moderate (5 – 9 requests/hour) High (> 10 requests/hour)	1,00 0,95 0,90 0,80	Literature
Tertiary	T01	Variability of bus dwell times at bus stops	Farside stop Nearside stop → Low Moderate High	1,00 1,00 0,95 0,90	Literature
	T02	Bus occupancy rate	< 15 persons 15 – 30 persons > 30 persons	0,95 1,00 1,05	Theoretical considerations
	T03	Utilization of countdown signals for pedestrians	No Yes	1,00 0,95	Literature
	T04	Number of traffic lanes on intersection exit links	Nearside stop or none Farside stop + 1 lane 2 lanes > 2 lanes	1,00 0,90 0,95 1,00	Theoretical considerations

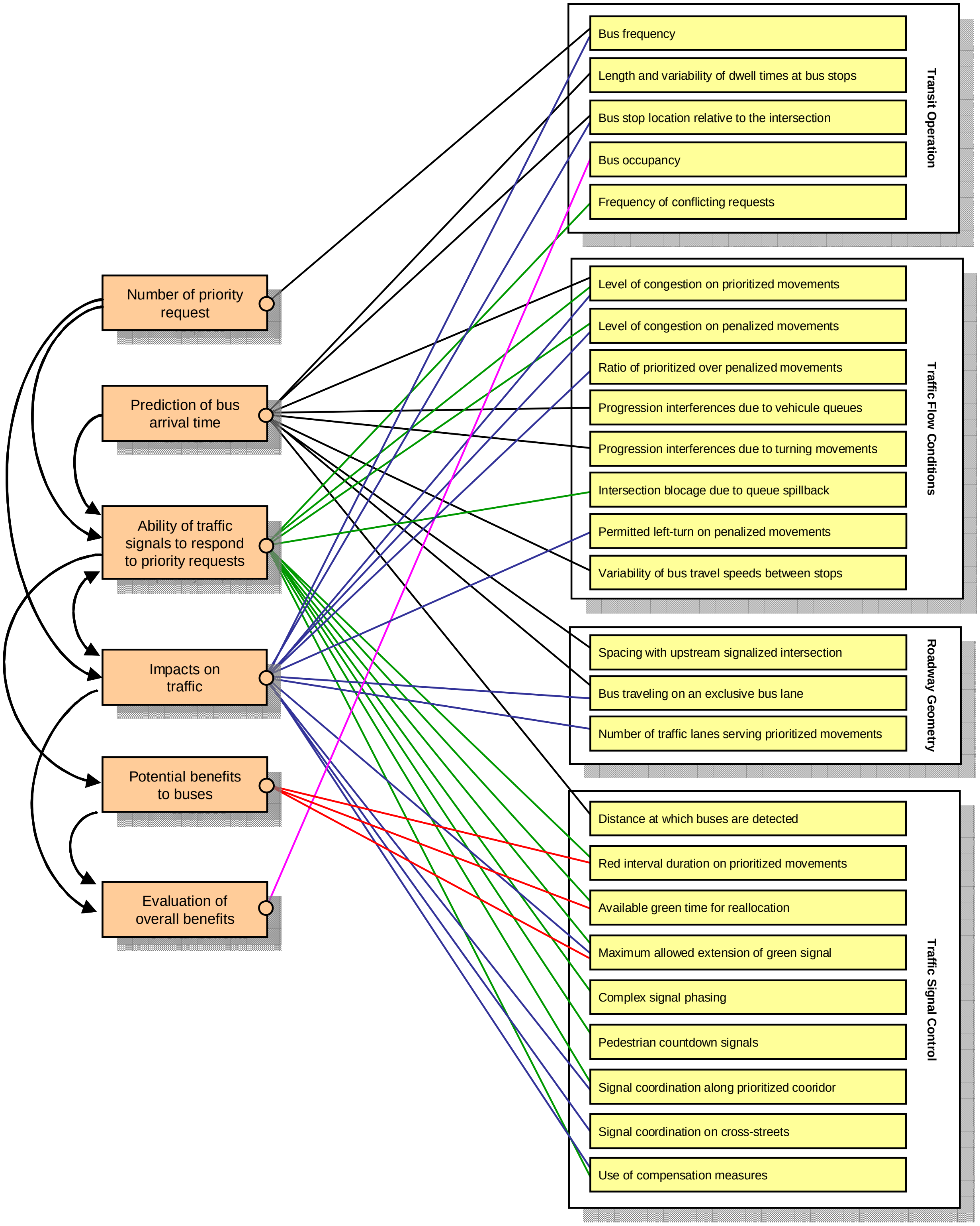
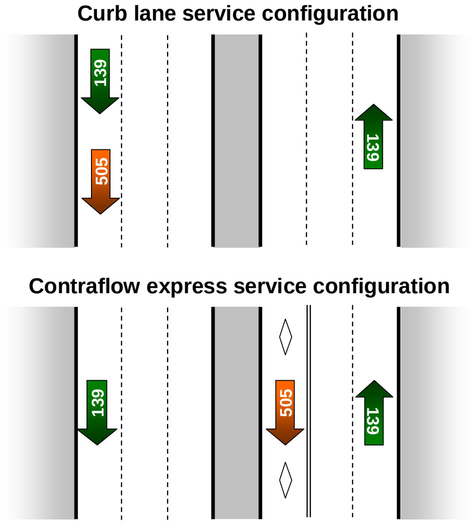


Figure 1 – Parameters impacting transit signal priority systems



Curb lane service configuration

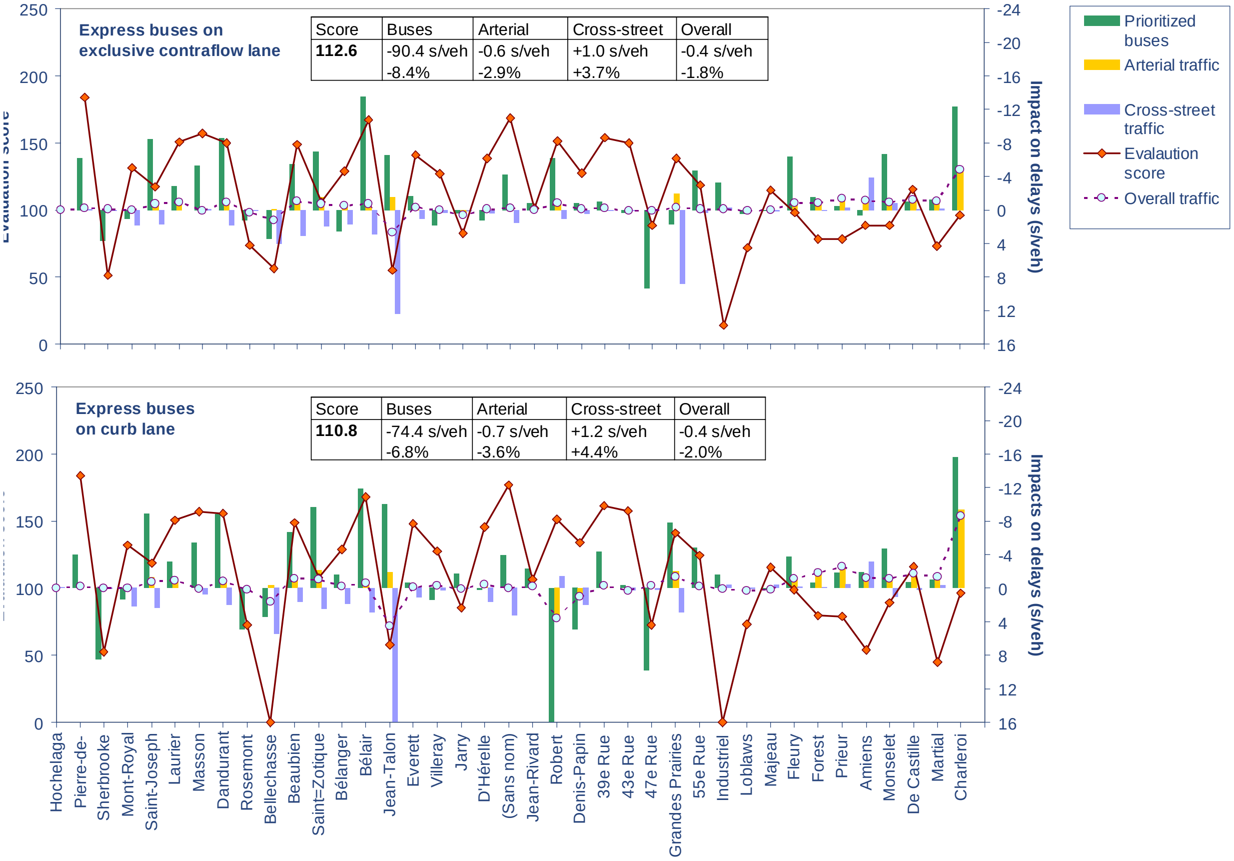
Contraflow express service configuration

Figure 2 – Transit service configurations for Pie-IX Boulevard test case

Score	Buses	Arterial	Cross-	Overall
148.0	-4.2 s/veh -29.7%	-1.4 s/veh -6.4%	+1.8 s/veh +6.5%	-0.9 s/veh -3.9%

Score	Buses	Arterial	Cross-	Overall
99.7	-8.8 s/veh -1.0%	-1.6 s/veh -7.9%	+1.8 s/veh +6.3%	-1.1 s/veh -5.3%

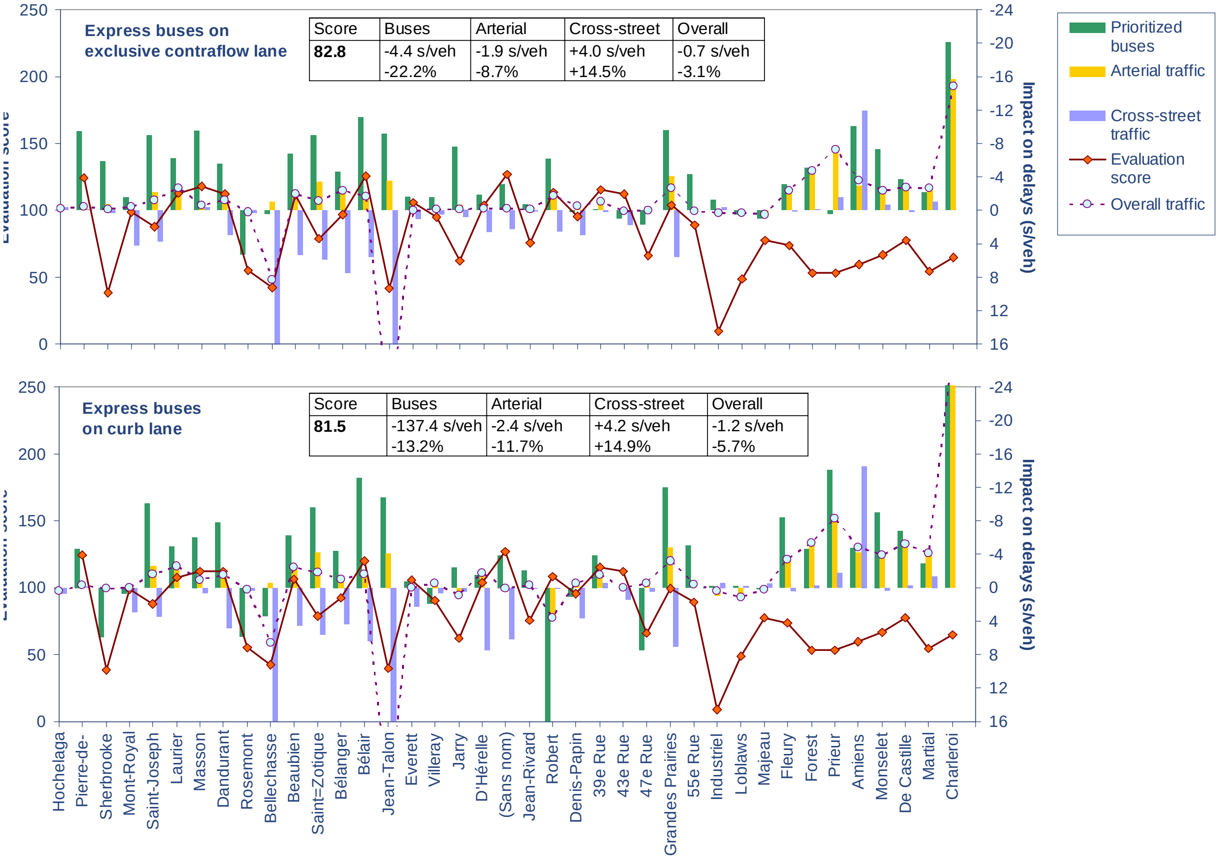
Figure 3 – Evaluations results for scenario providing priority to express buses only



Score	Buses	Arterial	Cross-street	Overall
112.6	-90.4 s/veh -8.4%	-0.6 s/veh -2.9%	+1.0 s/veh +3.7%	-0.4 s/veh -1.8%

Score	Buses	Arterial	Cross-street	Overall
110.8	-74.4 s/veh -6.8%	-0.7 s/veh -3.6%	+1.2 s/veh +4.4%	-0.4 s/veh -2.0%

Figure 4 – Evaluations results for scenario providing priority to regular buses only



Score	Buses	Arterial	Cross-street	Overall
82.8	-4.4 s/veh -22.2%	-1.9 s/veh -8.7%	+4.0 s/veh +14.5%	-0.7 s/veh -3.1%

Score	Buses	Arterial	Cross-street	Overall
81.5	-137.4 s/veh -13.2%	-2.4 s/veh -11.7%	+4.2 s/veh +14.9%	-1.2 s/veh -5.7%

Figure 5 – Evaluations results for scenario providing priority to express and regular buses