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Development and Evaluation of an Adaptive Transit Signal Priority Control with Updated Transit Delay Model

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ABSTRACT

Transit Signal Priority (TSP) strategies are widely used to reduce bus travel delay and increase bus service reliability. State-of-the-art TSP strategies enable dynamic (and optimal), rather than predetermined, TSP plans to reflect real-time traffic conditions. These dynamic TSP plans are called adaptive TSP. Existing adaptive TSP strategies normally use a performance index (PI), which is a weighted summation of all types of delays, to evaluate each candidate TSP plan and the weights to reflect the corresponding priority. The performance of adaptive TSP depends on three factors: delay estimation, weights determination and optimization formulation. In this context, there are three key academic contributions of this paper: 1. enhance an advance-detection-based bus delay estimation model; 2. develop a mechanism to dynamically adjust the PI weights to reflect the changing necessity of TSP under different conditions; and 3. formulate the TSP optimization into a quadratic programming problem with an enhanced delay-based PI to obtain global optimization using MATLAB solvers. In addition, an adaptive TSP simulation platform was developed using a full-scale signal simulator, ASC/3, in VISSIM. The optimal TSP plans are granted or rejected based on TSP events, such as check-in, check-out and multiple TSP requests. Through a case study in VISSIM, it was found that, compared with conventional active TSP strategies, the new adaptive TSP strategy could further reduce bus travel time, while maintaining a better balance of service on non-TSP approaches along a 7.4 kilometre bus corridor in Edmonton, Alberta, Canada.

Key words: Adaptive transit signal priority; Traffic operations; Traffic signal control; Optimization; Traffic simulation

INTRODUCTION

It is widely accepted that Transit Signal Priority (TSP) can reduce unintended bus delays at signalized intersections through extending the current green or truncating the current red upon the bus approach. Improving the effectiveness of TSP operations has been the subject of considerable research. In a previous report, it was estimated that TSP reduces unintended bus delay by 10-25% in urban areas *(1)*. A major controversy, though, is that TSP may bring excessive delays on non-TSP approaches, as their assigned greens are shortened. To leverage bus delay reduction and control delay increase, many researchers and manufacturers developed adaptive TSP, or dynamic TSP in other literature, to enable the dynamic adjustment of TSP plans *(2-4)*. Most adaptive TSP algorithms aim to solve an optimization problem, in which the objective function is the weighted summation of bus delays and traffic delays; variables are the greens constrained by the structure of signal controllers and other practical issues. Among all the existing adaptive TSP algorithms, there are three common flaws: 1. the bus delay estimations are often oversimplified and only represent certain special situations; 2. the overflow condition is simplified or even ignored; and 3. previous TSP plans are typically aimed at overall control delay, not just bus delay, at intersections. To address the aforementioned issues, a new bus delay model was designed based on advanced detection; this model was used to estimate bus delay, which then serves as a part of the objective function during TSP optimization. Second, the control delay at each approach (rather than overall control delay) was used in the objective function. There are key contributions of this paper: an enhancedmodel, which is suitable for more general traffic conditions, such as when buses share lanes with other vehicles; and a fully adaptive TSP algorithm, which includes dynamic adjustments of greens, rather than constant extensions and truncations, as in most conventional TSP operations.

The remainder of this paper is organized into sections: 1. a literature review regarding the adaptive TSP algorithm; 2. a new adaptive TSP control algorithm is described; 3. the new TSP algorithm is evaluated and compared with conventional active TSP operations along a 7.4 kilometre (km) bus corridor in Edmonton, Alberta, Canada; and 4. the paper is concluded with a results discussion and recommended future work.

LITERATURE REVIEW

Researchers and practitioners are dedicated to improving TSP performance and developing state-of-the-art adaptive TSP strategies. In 2000, Furth and Muller classified TSP strategies into three dimensions *(5)*: 1. passive TSP and active TSP; 2. partial TSP and full TSP; and 3. conditional TSP and unconditional TSP. These dimensions can be divided into two types: 1. an optimization problem, which includes objective functions, variables and their constraints: the final optimal TSP strategy is often reached by sophisticated calculation; 2. ad-hoc TSP strategies that aim to solve specific problems. Type 1 TSP strategies require advanced computation and the replacement or retrofitting of existing signal controllers; however, type 1 TSP strategies maximize the potential of new technologies and related theories. Type 2 TSP strategies require little changes to existing hardware, but may be less flexible in practice. Duerr optimized an adaptive TSP control strategy through minimizing the performance index (PI), which is composed of vehicle delay, vehicle stops, residual queues and overflow impact *(6)*. A major issue of Duerr's method is that signal timing impact was not considered in the function. Head et al. developed a decision model to optimize pre-emption *(7)*. In Head et al.'s model, the bus delay was defined as the time difference between when a bus sends the TSP request, and when the bus gets the green. He et al. used a heuristic search method to optimize the sequence of simultaneous pre-emption *(8)* and address a multimodal pre-emption issue *(9)*. In He et al.'s method, the authors used the same approach to calculate transit delay as in Head's model. Li developed an adaptive TSP algorithm using the mixed integer linear program (MILP) model to minimize a total weighted delay *(3)*. Li's model is as a variant of PI-based TSP optimization, in which the traffic delay is derived from the classic deterministic queuing model and the bus delay derives from the cumulative vehicle curve. Christofa et al. used personal delay as their objective, in which traffic and bus delay were both derived from the cumulative vehicle count curves and then weighted by occupancy *(2, 10)*. Stevanovic used a simulation-based optimization method and genetic algorithms to provide optimal TSP operations *(11-13)*. Furth et al. investigated the integration of bus schedule and signal control at major bus stops in simulation *(14)*.

In practice, although optimization can be achieved in computers and simulations, such optimization solvers are difficult to deploy in the field unless extensive software developments are made. To overcome this difficulty, for type 2 TSP strategies, a rule-based solution has been designed due to its practicability. Ekeila et al. proposed a Dynamic Transit Signal Priority (DTSP) system based on predicted bus arrival times and an evaluation of the candidate strategies *(15)*. Ma and Bai developed a service sequence optimizing approach to the issue of multiple bus priority requests *(16)*. In their system, the authors used the decision tree to set up the rules, and then selected the best “branch” according to the predefined objective function. Later, Zlatkovic et al. proposed another rule-based algorithm to resolve the issue of multiple TSP requests *(17)*.

MODEL DESCRIPTION

Objective Function

The objective of the proposed TSP system is to reduce bus delay at intersections, while maintaining an acceptable level of service to all traffic on all approaches. To reflect this objective, the objective function was designed, as shown in Equation (1) through Equation (3). The first item in Equation (1) refers to the weighted maximum control delay d_a among all approaches, and the second item refers to the weighted total bus delay $\beta\sum_N d_b$. Using the maximum control delay on one approach instead of the average control delay at intersections avoids a situation where using the average control delay at intersections may make the solver favor mainline traffic too much and increase the control delay on non-TSP approaches to an unacceptable level of service.

$$D = \alpha \max\left(d_{a,i}\right) + \beta\sum_N d_b \tag{1}$$

In Equation (1) through Equation (3), the weighting factor α and β are dependent on the sensitivity analysis. N stands for the number of simultaneous TSP requests. Some assumptions are made to simplify the discussion:

1. No residual queues in the beginning;
2. No phase re-service;
3. Slow buses do not generate moving bottlenecks;
4. No bus stops between check-in detector and stop line;
5. Any bus will cross the intersection within two cycles;
6. Fixed cycle length at the subject intersection;

7. Uniform traffic arrival and uniform driver behaviors in each traffic state; and
8. No significant acceleration and deceleration process.

Control Delay Estimation

The control delay estimation is based on the models recommended by the Highway Capacity Manual 2010 (Equation (2) through Equation (7)). Specifically, the uniform delay is expressed as:

$$UD = \frac{1}{2}C\frac{\left(1-g/C\right)^2}{1-\left(g/C\right)\min(X,1)} \qquad (2)$$

Following Webster's delay model *(18)*, the random delay is expressed as:

$$RD = \frac{1}{2v}\left(\frac{X^2}{1-X}\right) \qquad (3)$$

The sum of the uniform delay and the random delay are expressed as:

$$d_a = 0.9\left(UD + RD\right) \qquad (4)$$

Once the volume to capacity ratio (*X*) is larger than 1, overflow occurs. Then, an additional item needs to be added:

$$OD = \frac{T}{2}\left(X - 1\right) \qquad (5)$$

Under the overflow condition, the uniform delay is expressed as:

$$UD_0 = \frac{1}{2}C\left(1 - g/C\right) \qquad (6)$$

The average delay becomes:

$$d_a = UD_0 + OD \qquad (7)$$

Where:

- d_a: The average traffic delay with a unit of second per vehicle;
- UD : The uniform delay;
- RD : Random delay;
- OD: Overflow delay;

- C : Cycle length;
- g : Effective green time;
- v : Flow rate;
- X : v/c ratio or degree of saturation;
- T : Analysis period;

Bus Delay Estimation

The bus delay is estimated through the relationship between projected trajectory, queuing profile and signal timing. According to the shockwave theories, there are three shockwaves formed under uncongested traffic conditions due to the cyclic changes of traffic signals *(19)*: queue formation (v_1), queue discharge (v_2) and queue clearance (v_3). As shown in Figure 2, these three shockwaves form two triangle shapes within each cycle. The shockwave speed for these three states can be calculated as:

$$v_1 = \left|\frac{0-q_a}{k_j-k_a}\right|; v_2 = \left|\frac{q_m-0}{k_m-k_j}\right|; v_3 = \left|\frac{q_m-q_a}{k_m-k_a}\right| \tag{8}$$

Where,

- q_a, k_a, arriving traffic volume and density;
- k_j, jam density;
- q_m, k_m, capacity volume and density;

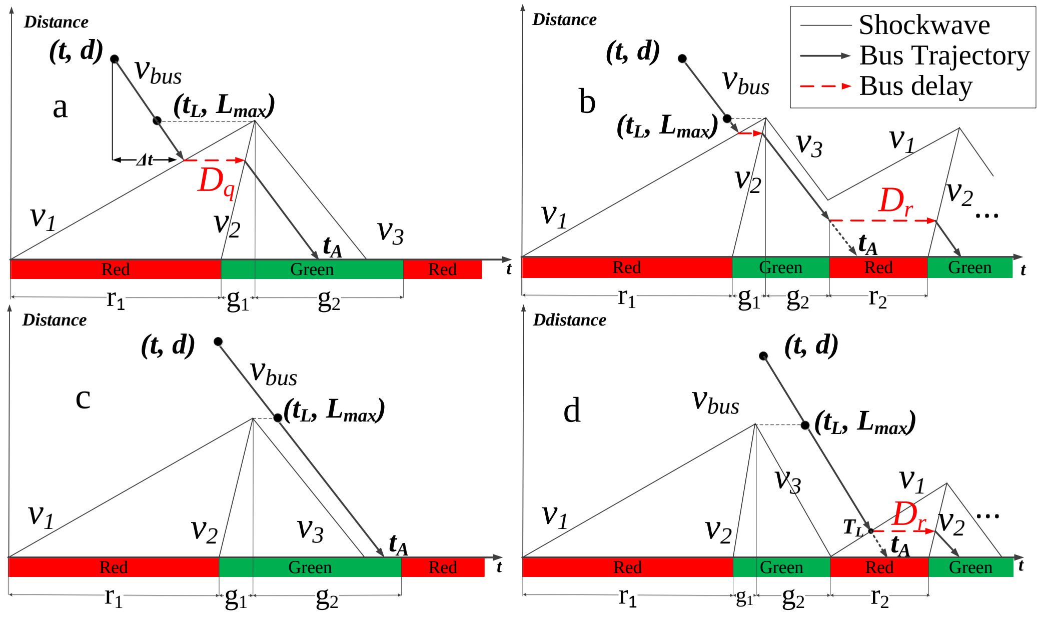

FIGURE 1 Four Bus Delay Scenarios for Estimation.

Depending on when the bus reaches the detector, four possible scenarios could occur, as shown in FIGURE 1. Three types of bus delays could possibly be generated: the bus queuing delay (D_q), which is caused by the bus joining and waiting in the queue; the bus waiting delay (experienced red) (D_r), which is when buses cannot cross within one cycle and have to wait for the next cycle; and the bus moving delay (D_d), which is generated when the bus's desired speed is higher than the capacity speed, in which case buses must slow down and join the moving queue. In summary, the bus delay can be expressed as:

$$d_b = \theta_1 D_q + \theta_2 D_r + \lambda D_d \tag{9}$$

θ and λ are flag parameters with a value of (0,1). λ is equal to 1 only if the traffic is under a high-speed-limit condition ($v_{bus} > v_m$). θ is determined by when the bus reaches the location of maximum queue length (t_L) and when the bus arrives at the stop line (t_A). θ's value can be expressed as:

- If ($t_L < r_1 + g_1$)

  Then $\theta_1 = 1$ otherwise $\theta_1 = 0$;
- If ($t_A < r_1 + g_1 + g_2$)

  Then $\theta_2 = 0$ otherwise $\theta_2 = 1$;
- If ($t_A > r_1 + g_1 + g_2$)

Then $\theta_1 = 0$ otherwise $\theta_2 = 0$;

t_L and t_A can be calculated, as shown in Equation (12) and (15):

$$t_L = t + \frac{\left(d - L_{\max}\right)}{v_{bus}} \tag{10}$$

$L_{\max}$, which represents the maximum queue length, can be derived as:

$$v_1\left(r_1 + g_1\right) = v_2 g_1 \Rightarrow g_1 = \frac{v_1 r_1}{v_2 - v_1} \Rightarrow L_{\max} = \frac{v_1 v_2 r_1}{v_2 - v_1} \tag{11}$$

$$d = v_1\left(t + \Delta t\right) + v_{bus}\Delta t \Rightarrow \Delta t = \frac{d - v_1 t}{\left(v_1 + v_{bus}\right)} \tag{12}$$

$$t_A = \begin{cases} t + D_q + \dfrac{d}{v_{bus}}, v_{bus} \le v_m \\ t + \Delta t + D_q + \dfrac{v_1\left(t + \Delta t\right)}{v_m}, v_{bus} > v_m \end{cases} \tag{13}$$

The waiting bus delay D_q is calculated as:

$$D_q = \frac{v_1\left(t + \Delta t\right)}{v_2} + r_1 - \left(t + \Delta t\right) = r_1 - \left(\frac{v_2 - v_1}{v_2}\right)\left(\frac{v_{bus} t + d}{v_1 + v_{bus}}\right) \tag{14}$$

The waiting delay (experienced red) D_r is calculated as:

$$d = \left(T_L - r_1 - g_1 - g_2\right)v_1 + \left(T_L - t\right)v_{bus} \Rightarrow T_L = \frac{d + \left(r_1 + g_1 + g_2\right)v_1 + v_{bus} t}{v_1 + v_{bus}} \tag{15}$$

$$D_r = \begin{cases} r_2 + \dfrac{(t_A - r_1 - g_1 - g_2 - r_2)v_m}{v_2}\ (t_L < r_1 + g_1) \\ \dfrac{\left(T_L - r_1 - g_1 - g_2\right)v_1}{v_2} + r_1 + g_1 + g_2 + r_2 - T_L\ (t_L > r_1 + g_1) \end{cases} \tag{16}$$

In high-speed-limit traffic conditions, a bus tends to drive at a higher speed v_{bus}. However once the bus joins the queue, the bus will have to follow the capacity speed v_m, lower than v_{bus}, generating the moving bus delay, D_d, as illustrated in FIGURE 2. v_m can be either directly observed in the field or calculated according to traffic stream models.

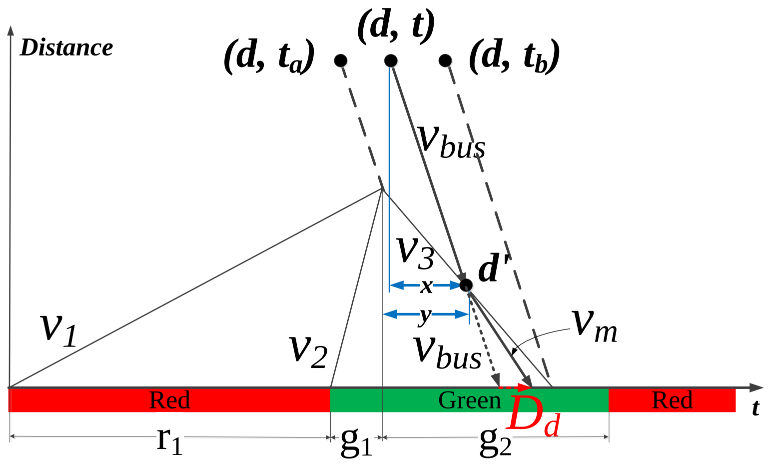

FIGURE 2 Illustration of Additional Delay Under High-Speed Conditions.

D_d can be calculated as:

$$D_d = \begin{cases} \dfrac{v_1(t+\Delta t)}{v_m} - \dfrac{v_1(t+\Delta t)}{v_{bus}}, & t_L < r_1 + g_1 \\ \dfrac{d - v_{bus}x}{v_m} - \dfrac{d - v_{bus}x}{v_{bus}}, & t_L > r_1 + g_1 \end{cases} \quad (17)$$

$$x = \frac{d - L_{\max} + v_3(t - r_1 - g_1)}{v_{bus} - v_3} \quad (18)$$

All symbols in Equations (11) through Equation (20) are defined, as shown in FIGURE 1 and FIGURE 2.

Among the three types of bus delays, the bus delay model by Head et al. covers the waiting delay *(7, 8)* and the bus delay models by Li et al. *(20)* and Christofa et al. cover the queuing delay and waiting delay. No previous model covers the moving delay, and at high-speed intersections, the bus moving delay may be significant.

Constraints

The variables in the optimization are green durations. The constraints are composed of the physical structure of signal controllers and actual traffic conditions. In North America, the commonly accepted constraints are composed of three parts: maximum and minimum greens; pedestrian settings; and cycle length and NEMA dual ring structure. The green duration constraints have been extensively defined in other literature *(7)*; green duration constraints can be expressed as:

$$\max\left(\lambda\left(g_{walk}+g_{pedclearance}\right),g_i^{\min}\right)\le g_i\le\max\left(\lambda\left(g_{walk}+g_{pedclearance}\right),g_i^{\max}\right)\\(i=1,2,3,\dots,8) \tag{19}$$

Where:

- g_i : green duration time;
- $g_i^{\min}$: minimum green;
- $g_i^{\max}$: the maximum green;
- g_{walk} : walk time;
- $g_{pedclearance}$: pedestrian clearance; and
- λ : flag variable (0: no pedestrian call; 1: pedestrian call);

In the standard ring structure, the total green time in each ring should be equal to the cycle length as:

$$\sum_{i=1}^{4}\left(g_i+y+ar\right)=C;\\\sum_{j=5}^{8}\left(g_j+y+ar\right)=C; \tag{20}$$

The barrier constraint restricts ring 1 and 2; the same side of the barrier should have the same duration, as shown in:

$$\begin{cases}g_1+g_2=g_5+g_6\\g_3+g_4=g_7+g_8\end{cases} \tag{21}$$

Where:

- C : Cycle length;
- g_i : Green duration of phase *i*;
- y : Yellow time; and
- ar : All-red time;

Optimization Formulation

The objective function in Equation (1) is approximately quadratic and all the constraints are linear. A sequential quadratic programming (SQP) solver in Matlab, an iterative optimizing method (1,000 iterations were used during optimization) was used to obtain the real-time optimal TSP plan. The necessary inputs for the optimization were retrieved through VISSIM COM and the optimal TSP plans were downloaded to the ASC/3 controller. The optimization problem was formulated as:

$$\min_{\mathbf{g}} \quad D = \alpha \max\left(d_a(\mathbf{g})\right) + \beta \sum\nolimits_N d_b(\mathbf{g})$$

$$\text{subject to: } \begin{cases} g_i - \max\left(\lambda\left(g_{walk} + g_{pedclearance}\right), g_i^{\max}\right) \leq 0 \\ \text{-}g_i + \min\left(\lambda\left(g_{walk} + g_{pedclearance}\right), g_i^{\min}\right) \leq 0 \\ \sum_{i=1}^{4}\left(g_i + y + ar\right) - C = 0 \\ \sum_{j=5}^{8}\left(g_i + y + ar\right) - C = 0 \\ g_1 + g_2 - g_5 - g_6 = 0 \\ g_3 + g_4 - g_7 - g_8 = 0 \end{cases} \tag{22}$$

The control delay and bus delay were calculated using Equation (2) through Equation (18). The weights were determined according to a sensitivity study. In practice, users may develop their own solvers or use alternative solvers to reach the optimal TSP plan.

SIMULATION CASE STUDY: PERFORMANCE EVALUATION OF ADAPTIVE TSP SYSTEMS

This task aims to evaluate the performance of the proposed adaptive TSP and compare it to a conventional active TSP strategy with green extension or red truncation. Since deploying such an innovative system in the field is unrealistic at this time, all the performance analyses and evaluations were conducted in a fine-grained simulation engine. The evaluation and comparison are divided into two categories: 1. the corridor level, which focuses on the total bus travel time and average bus delay along a 7.4 kilometre bus corridor in Edmonton, Alberta; and 2. individual intersections, including traffic control delay, bus delay, etc.

Simulation Platform Architecture

The simulation platform architecture is illustrated in FIGURE 3. VISSIM with the ASC/3 module, a full-scale signal emulator, works as a traffic simulator. The real-time bus data for optimizing signal timing was sent and received via COM interfaces. Whenever a bus was detected by the fixed-spot advance bus detector, the "Mediator" module collected all necessary traffic data via VISSIM and signal timings via the NTCIP standards supported by the ASC/3 module *(21)*. Once such information was collected, it was sent to the "Optimizer" module to obtain the optimal signal timing to minimize the PI. The optimizer updated the quadratic problem, obtained the optimal TSP plans and then sent that new TSP timing back to the Mediator via the .NET framework. Finally, the Mediator module sent the optimal TSP plans back to the simulator through a series of NTCIP messages. Specifically, the current timing plan was first saved in a different split plan in ASC/3 and then replaced with the new optimal TSP signal timing. Once the TSP timing plans expired (e.g., buses check out or maximum timer is reached), the Mediator recovers the original signal timings. In case of multiple TSP requests, the optimizer recalculated the optimal TSP timing based on the events of TSP calls and updated the signal timing accordingly. As a result, a granted TSP may be cancelled within the same cycle if the buses on other approaches appear to have a higher TSP need. Once a TSP request is granted and finished, the controller recovers the original signal timing and inhibits the TSP requests for 2 cycles to ensure that the general traffic can cross the intersection efficiently. During TSP operations, the cycle length and offset were not changed; therefore, the coordination on the mainline was maintained.

In this study, new TSP timings did not change the phasing sequence nor skip phases. Future studies will focus on more aggressive adaptive TSP strategies.

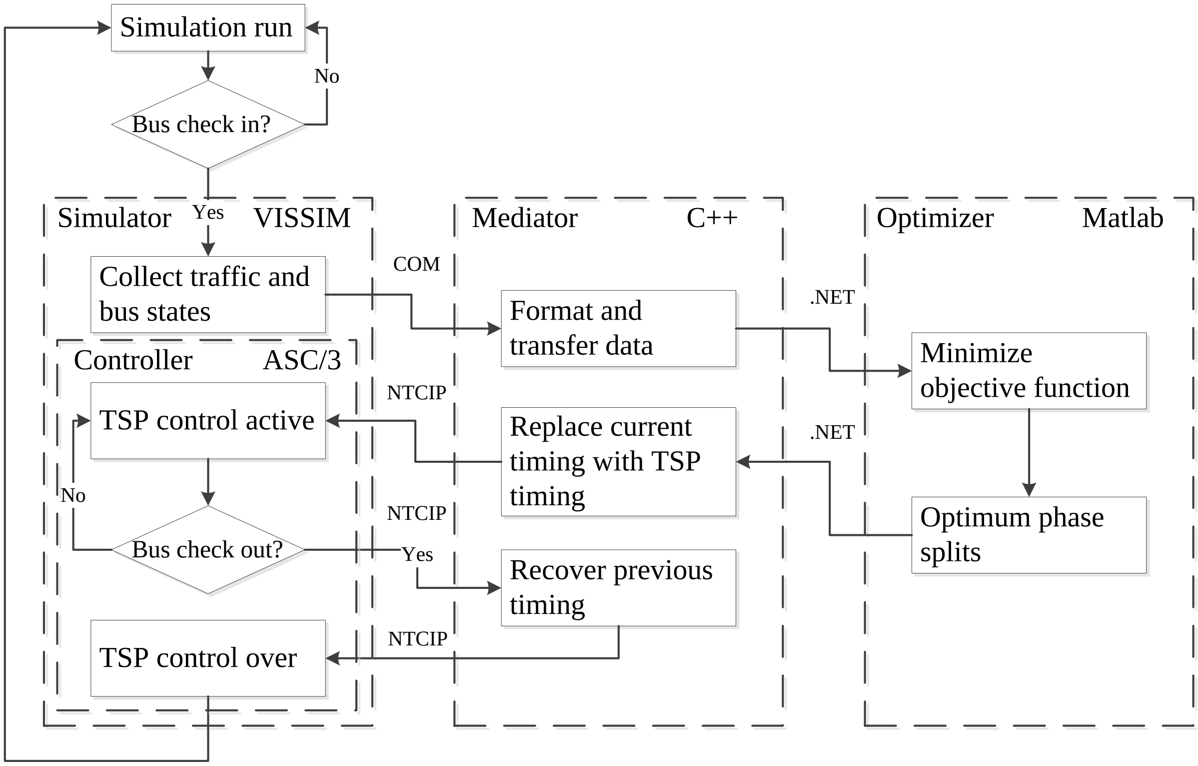

FIGURE 3 Architecture of the Proposed Adaptive TSP Systems.

Case Study in Simulation: the Southeast TSP Corridor in Edmonton, Alberta, Canada

Figure 3 shows the scope of the southeast bus corridor, which starts from the Low Level Bridge and runs to the Millgate Transit Centre; it is 7.4 kilometre. On the corridor, there are eight signalized intersections separated by fair distances; the phasing sequence is shown in Table 1. The traffic turning movements and signal timings were obtained from the Edmonton Transit System (ETS) of the City of Edmonton. The selected study period was for the transit PM peak hours from 15:30-17:30 when pedestrian calls are very low. The corresponding bus schedule was also retrieved from ETS. In total, there are 25 bus routes that run through the whole or part of the study corridor and average headway during peak hours is 15 minutes. Thirty buses are equipped with TSP transponders. The simulation network was also well calibrated by adjusting the driver behaviors to ensure the link travel times and maximum queue lengths at key intersections under the current traffic conditions and signal timings were consistent with field observations. According to the provided traffic volumes and field observations, the maximum queue lengths at all intersections were all shorter than 200 meters; therefore, the advance bus detectors were uniformly placed 250 meters from the stop lines. This will also leave enough time for the solvers to reach the optimal TSP timings.

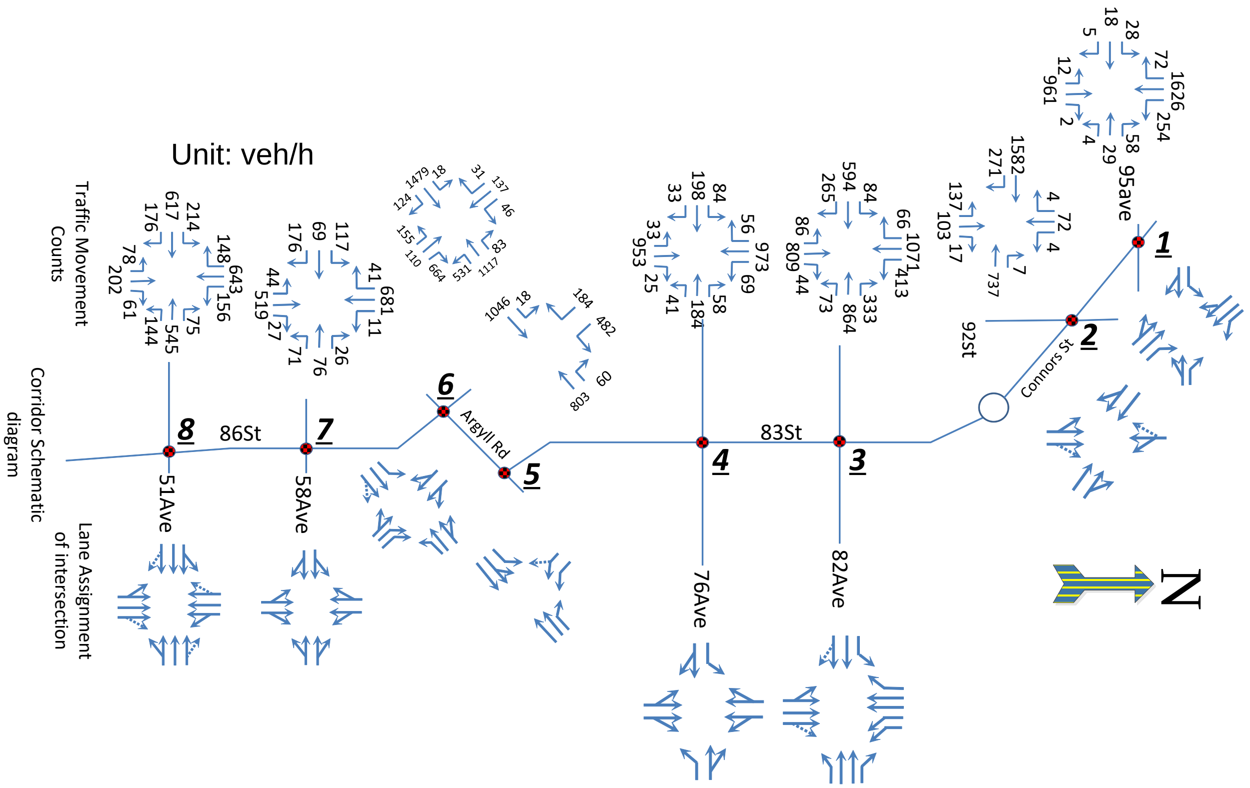

FIGURE 4 The Scope of Southeast TSP Corridor in Edmonton, Alberta, Canada.

TABLE 1 Signal Timing at Each Intersection.

No	Intersection	Cycle	Offset	Timing Plan
1	95ave& Connors Rd	100	79	Φ2 90s, Φ4 10s Φ5 29s, Φ6 61s, Φ8 10s
2	92st& Connors Rd	100	0	Φ2 12s, Φ4 88s Φ6 12s, Φ8 88s
3	82ave& 83st	100	96	Φ2 69s, Φ4 31s Φ5 17s, Φ6 52s, Φ8 31s
4	76ave& 83st	50	44	Φ2 34s, Φ4 16s Φ6 34s, Φ8 16s
5	Argyll& 83st	100	24	Φ2 23s, Φ3 54s, Φ4 23s Φ8 77s
6	Argyll& 86st	100	92	Φ2 28s, Φ3 8s, Φ4 64s Φ6 28s, Φ7 33s, Φ8 39s
7	58ave& 86st	50	8	Φ2 29s, Φ4 21s Φ6 29s, Φ8 21s

8	51ave& 86st	100	90	Φ1 10s, Φ2 33s, Φ3 18s, Φ4 39s Φ5 17s, Φ6 26s, Φ7 14s, Φ8 43s

Sensitivity Analysis to Determine the Weighting Factor

The first step was to find a suitable value for the weighting factor α and β. The reasonable approach is to conduct a sensitivity test and determine the most appropriate relationship between α and β to balance the bus benefits and general traffic interferences. The value of β/α determines the priority of buses; therefore, the optimal TSP timings. To investigate how the factors perform, a series of preliminary simulation runs was conducted. The test range of β/α is from 10-100 with 10 increments. Set $\beta/\alpha = 1$ as the reference case, because in this case, the bus is the same as a general vehicle.

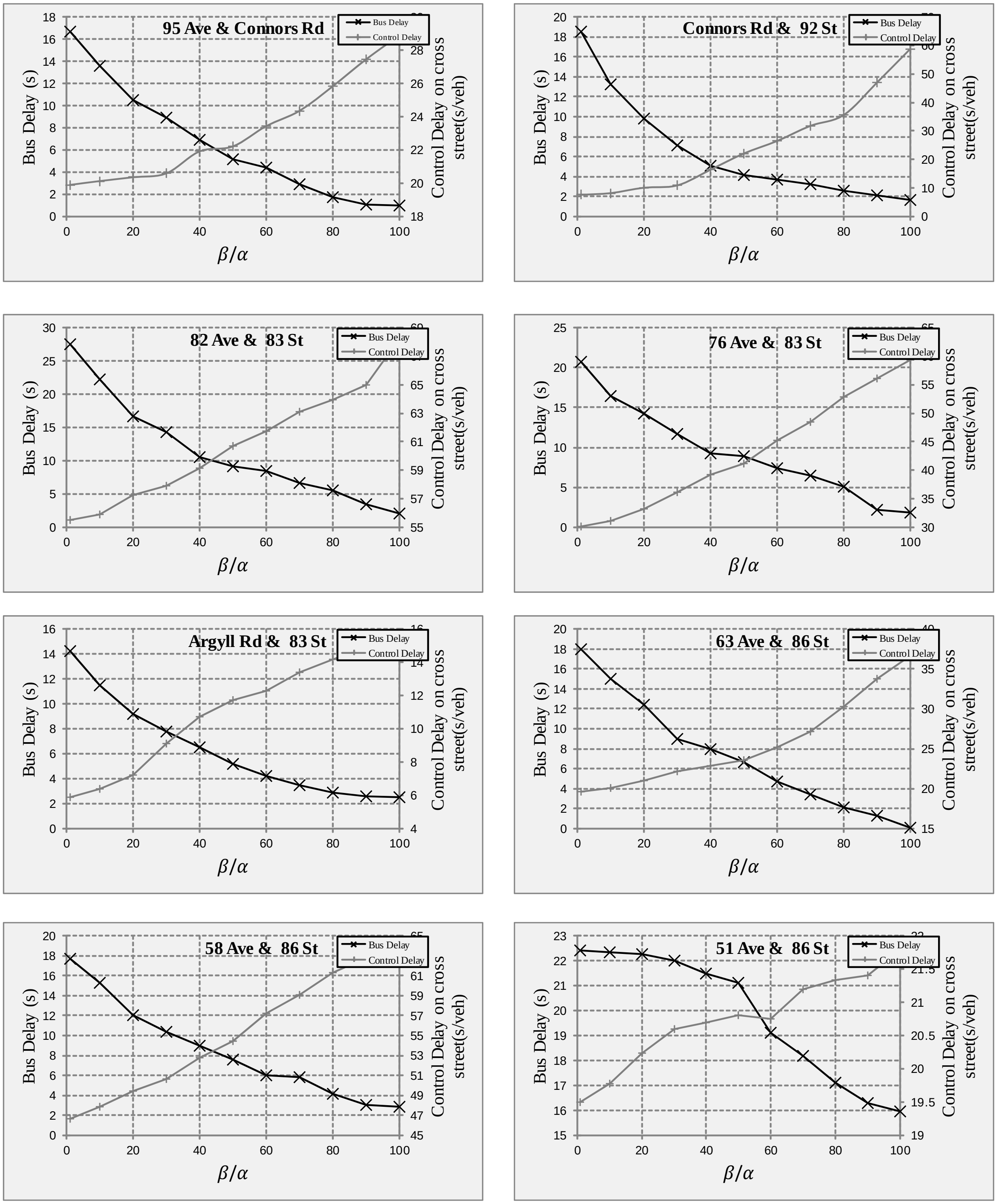

FIGURE 5 Sensitivity Analysis of the Weighting Factor.

FIGURE 5 shows the relationship between the β/α and the bus and the control delay for each intersection, assuming all buses could be granted TSP operations. As the β/α increases, the bus delay (also the general vehicles' delay on the mainline) decreases because of the higher weight (priority) given to the bus. However, at the same time, the control delay increased and became faster and faster. Therefore, the best value of β/α belongs to the location where the bus delay reduction and control delay increment are balanced.

Results Analysis

Three scenarios were analyzed: 1) baseline signal timing (the current signal timing without TSP); 2) current signal timing with the conventional active TSP system; 3) current signal timing equipped with the new adaptive TSP system. The conventional active TSP strategy has a typical setting of 10-second maximum green extension and 5-second guaranteed green on other phases, which can be set up in the ASC/3 emulator. Each scenario was simulated 10 times with a common set of random seeds. The selected β/α values were varied at different intersections. There were three Measures of Effectiveness (MOEs): 1. the total bus travel time along the bus corridor; 2. the bus delay at each intersection; and 3. the worst control delay among all approaches at each intersection.

The results are shown in TABLE 2, TABLE **3**, and TABLE **4**. Comparing the non-TSP scenario to both the active and adaptive TSP scenario shows significant bus travel time savings (see TABLE 2). The mean value of the total travel time shows adaptive TSP saves about 60-80 seconds more than active TSP on the whole corridor. It was also found that both active TSP and adaptive TSP reduce bus delay, as shown in TABLE **3**. On the other hand, as shown in TABLE **4**, it was found that, compared to non-TSP scenarios, TSP scenarios can cause an increase of control delay at some intersections; however, adaptive TSP strategies are able to mitigate this problem. To investigate the significance of improvement by the proposed adaptive TSP, a statistical study was conducted: the t-test. In the t-test, it was assumed that the sample of the results followed the normal distribution and 0.05 was selected as the significance level. The comparisons of MOEs can also be found in TABLE 2, TABLE **3**, and TABLE **4**.

As shown in TABLE 2, both the active TSP and the proposed adaptive TSP strategies significantly reduce bus travel time on the corridor, and the adaptive TSP strategy significantly outperforms the active TSP strategy. As shown in TABLE 4, the adaptive TSP strategy has a significantly better performance in bus delay reduction. As shown in TABLE 5, the active TSP strategy increases the control delay on non-TSP approaches, whereas the proposed adaptive TSP strategy mitigates this problem by balancing the control delay on the mainline and on the side streets.

TABLE 2 Total Bus Travel Times on the Southeast Corridor.

Control Type	Southbound		Northbound	
	Average total travel time (s)	Time saving	Average total travel time (s)	Time saving
Baseline	1089.7	N/A	1086.6	N/A
Active	999.7	90	1024.4	62.2
Adaptive	1010.5	79.2	1046.6	40
t value	5.98		2.83	
t critical value (two tail)	2.13		2.13	
Confidence Level	95%		95%	
p value	1.12e-4		1.81e-4	
Significant improvement?	Yes		Yes	

TABLE 3 Bus Delay at Individual Intersections.

No.	1	2	3	4	5	6	7	8
Intersection	**95 Ave & Connors Rd**	**Connors Rd & 92 St**	**82 Ave & 83 St**	**76 Ave & 83 St**	**Argyll Rd & 83 St**	**63 Ave & 86 St**	**58 Ave & 86 St**	**51 Ave & 86 St**
	Delay (sec)							
Direction	SB	SB	SB	SB	SB	SB	SB	SB
Baseline	11	7.3	15.8	10.4	6.2	25.4	6.4	25
Active TSP	6.7	2.5	8.3	5.2	3.6	17.8	3	15.7
Saving	4.3	4.8	7.5	5.2	2.6	7.6	3.4	9.3
Adaptive	8	4.7	9.3	7.2	6.2	20.4	5.3	18.1
Saving	3	2.6	6.5	3.2	0	5	1.1	6.9
t value	2.03	4.22	3.47	1.5	0.02	1.54	1.06	2.71
t critical value (two tail)	2.1							
Confidence Level	95%							
p value	5.9E-03	8.9E-04	5.0E-03	1.5E-01	9.8E-01	1.4E-01	3.1E-01	1.8E-02
Significant improvement?	No	Yes	Yes	No	No	No	No	Yes
	Delay (sec)							
Direction	NB	NB	NB	NB	NB	NB	NB	NB
Baseline	19.8	7.8	19.7	7.4	5.4	13.4	6.9	36.7
Active	10.8	2.1	13	6.9	3.7	4.1	5.4	23.7
Saving	9	5.7	6.7	0.5	1.7	9.3	1.5	13

Adaptive	12	3.2	14.1	4.2	3.1	13.5	4	25.6
Saving	7.8	4.6	5.6	3.2	2.3	-0.1	2.9	11.1
t value	4.83	5.92	2.28	1.77	2.76	0.38	3.93	2.78
t critical value (one tail)	2.1							
Confidence Level	95%							
p value	2.6E-04	1.0E-04	3.6E-02	9.7E-02	1.5E-02	7.1E-01	1.7E-03	1.6E-02
Significant improvement?	Yes	Yes	Yes	No	Yes	No	Yes	Yes

TABLE 4 Intersection Level of Service and Control Delay.

No.	**1**				**2**				**3**			
Intersection	95 Ave & Connors Rd				Connors Rd & 92 St				82 Ave & 83 St			
	Average Vehicle Control Delay(seconds/vehicle)											
	LOS	Main Line	LOS	Side Street	LOS	Main Line	LOS	Side Street	LOS	Main Line	LOS	Side Street
Baseline	A	8.6	C	24	B	11.45	C	34.2	C	27.7	E	58.7
Active	A	7.75	C	28.8	A	9.25	D	42.7	C	24.3	E	76.25
Saving		0.85		-4.8		2.2		-8.5		3.4		-17.55
Adaptive	A	8.45	C	23.4	B	10.2	C	32.95	C	25	E	52.5
Saving		0.15		0.6		1.25		1.25		2.7		6.2
t value		0.19		0.04		1.04		0.039		0.67		0.63
t critical value (two tail)	2.1											
Confidence Level	95%											
p value		0.84		0.96		0.31		0.97		0.51		0.53
Significant change?		No		No		No		No		No		No
No.	4				5				6			
Intersection	76 Ave & 83 St				Argyll Rd & 83 St				63 Ave & 86 St			
	Average Vehicle Control Delay(seconds/vehicle)											
	LOS	Main Line	LOS	Side Street	LOS	Main Line	LOS	Side Street	LOS	Main Line	LOS	Side Street
Baseline	A	7.25	D	43.1	B	11.7	A	7.95	C	25.6	C	33.6
Active	A	3.4	D	49	B	10.35	A	8.55	C	20.85	D	45
Saving		3.85		-5.9		1.35		-0.6		4.75		-11.4
Adaptive	A	6.4	D	41.5	B	10.4	A	7.2	C	23.35	C	27.5
Saving		0.85		1.6		1.25		0.75		2.25		6.05
		3.4		49		10.35		8.55		20.85	D	45
t value		0.03		0.208		1.13		0.84		1.63		1.41
t critical value (two tail)	2.1											
Confidence Level	95%											
p value		No		No		No		No		No		No
Significant change?	A	7.25	D	43.1	B	11.7	A	7.95	C	25.6	C	33.6
No.	7				8							
Intersection	58 Ave & 86 St				51 Ave & 86 St							
	Average Vehicle Control Delay(seconds/vehicle)											
	LOS	Main Line	LOS	Cross Street	LOS	Main Line	LOS	Cross Street				

Baseline	A	8.5	E	68.9	C	28.6	C	29.6
Active	A	2.65	E	72.85	B	19.0	C	25.5
Saving		1.25		-12.3		2.8		-5.25
Adaptive	A	5.25	E	52.75	B	19.6	C	21.95
Saving		-1.35		7.8		2.2		-1.7
t value		0.74		1.42		0.51		0.8
t critical value (two tail)	2.1							
Confidence Level	95%							
p value		0.099		0.62		0.70		0.20
Significant change?		No		No		No		No

CONCLUSIONS AND FUTURE WORK

In this paper, an optimal TSP strategy was formulated into a quadratic programming problem. In the objective function, a new bus delay estimation method was developed based on advanced bus detectors, the weighted summation of the largest control delay on all approaches and the total bus delay. A simulation platform was developed to implement the adaptive TSP strategy via ASC/3 software, a full-scale signal emulator in VISSIM. In the case study, the performance of conventional active TSP and the proposed adaptive TSP was compared along a 7.4 kilometre bus corridor in Edmonton, Alberta. The results show that the adaptive TSP strategy significantly outperforms the conventional active TSP in reducing bus travel times and leveraging the control delays on bus approaches and non-bus approaches.

Since the queuing profile was derived from the assumption of uniform traffic arrivals, the proposed adaptive TSP strategy will be more effective at isolated or far-spaced intersections than at coordinated intersections. Future studies will extend this adaptive TSP strategy to cover those intersections where the traffic arrives in platoons.

During simulation, each TSP optimization took around 3-5 seconds. It barely met the requirements because the travel time from advanced bus detectors to the queue end was mostly longer than 5 seconds. Future studies will explore more efficient optimizing algorithms to reduce the optimizing time for more complex situations, such as taking the phasing sequence optimization into account or coordinated adaptive TSP strategies at multiple intersections.

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