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A real-time optimisation-based bus priority control for isolated intersections

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Abstract

Transit signal priority (TSP) is a growing area of the transportation system. One problem with the existing optimization-based TSP at intersections is that signal priority strategies that consider mixed traffic and minimize adverse impact on general traffic are not considered. In this study, a TSP strategy is proposed that takes into account the reduction of average bus passenger delay and minimizing adverse delay on other traffic users at intersections. This strategy includes two types of TSP actions: green extension and inserted bus phase. The Harmony search (HS) algorithm was employed to find optimal values of two control parameters, including green extension time and inserted bus phase duration. The case study for this paper was carried out using a four-approach intersection of Old Cleveland Corridor in Brisbane. The authors used Aimsun simulation to evaluate the efficiency of proposed TSP strategy. Three scenarios were evaluated under the same traffic conditions, including no TSP, rule-based TSP, and the proposed optimization-based TSP. The simulation results show that the proposed TSP can significantly reduce the average bus passenger time and minimize the average passenger delay for other general traffic compared to no TSP and rule-based TSP.

Keywords: Traffic control, transit signal priority, optimization-based signal control, mixed-integer nonlinear model.

1. Introduction

Public transport (PT) is considered an efficient approach to move people and reduce traffic congestion because of its large passenger occupancy compared with passenger cars (Wang et al., 2017). PT ridership can be encouraged by improving frequency and/or reliability. Transit Signal Priority (TSP) control, developed since the late 1960s (Company and Housing, 1968), has been recognised as one of the most promising mechanisms to reduce transit travel time and increase its reliability along arterials. TSP mainly uses green extension, red truncation, and transit phase insertion control strategies. Under green extension, green time is extended to serve a PT vehicle that is expected to reach an intersection shortly after the programmed green time is ending. Red truncation enables the intersection controller to transition earlier to a phase that will serve a PT vehicle approaching the intersection. Under transit phase insertion, a dedicated phase is incorporated into the regular sequence of phases to facilitate the movement of PT vehicles.

Over the last two decades, many studies have evaluated the performance of TSP on reducing bus travel time. Vlachou et al. (2010) proposed an unconditional rule-based TSP including green extensions with 10 second maximum green time to reduce overall bus travel time. Zlatkovic et al. (2012) tested unconditional rule-based TSP including green extension and red truncation on a corridor with an exclusive bus lane to reduce delay at intersections. Bagherian et al. (2015) proposed an unconditional rule-based TSP including red truncation and green extension, that was evaluated on a Redland Bay corridor with three intersections in Brisbane. Some studies have investigated how various green extension durations could impact bus travel time. For example, Stevanovic et al. (2008) tested 20 seconds or 20% of cycle length for maximum green extension and red truncation. The study employed a Genetic Algorithm to find optimal green extension and red truncation value with minimum average person delay. Truong et al. (2017) proposed maximum priority time of 10 seconds for green extension and red truncation strategies. An estimated travel time with a slack time was used to predict the arrival interval of the bus at the stop line. Oguchi et al. (2017) limited maximum green extension and red truncation to 25 seconds. Unconditional rule-based TSP provides priority regardless of the status of the PT vehicles (e.g., the vehicle may be well in advance of its schedule; thus, it does not need priority). Therefore, conditional rule-based TSP was developed to consider the schedule or headway adherence of the arriving PT vehicle. Vujić et al. (2015) proposed a conditional rule-based TSP including green extension, which only granted TSP to a PT vehicle behind scheduled arrival time at the next bus stop.

Rule-based TSP only focuses on minimizing bus travel time at an intersection or corridor, which ignores potential adverse impacts on side-streets. The major disadvantage of rule-based TSP is that it can cause large delay to side street traffic. Hence, optimization-based TSP was proposed to overcome this limitation. To minimise the gap between the estimated bus delay and the permitted bus delay as defined by the bus operation system, Ma et al. (2010) developed a conditional optimization-based TSP to generate the optimal combination of priority for groups of intersections based on a bus delay prediction model. Li et al. (2011) developed an adaptive TSP optimization model to optimize green splits for three consecutive cycles to minimize the weighted sum of transit vehicle and other traffic delay. A regression model was proposed to predict bus arrival time at a downstream stop. Hu et al. (2014) utilized connected vehicle technology based on two-way communications between transit buses and traffic signals to provide more accurate bus arrival time at bus stops. The proposed TSP generated a timing plan that aimed to minimize total person delay at intersections based on the predictive bus arrival time. Teng et al. (2019) proposed a transit signal priority controlling method including green extension, red time truncation and phase insertion for the single-ring sequential phasing under a CV environment to minimize the time deviations for the non-transit phase. Probe vehicle data was utilized to estimate the queue length for intersections. Truong et al. (2019) formulated a stochastic optimization model to find the optimal TSP parameters including green extension duration and early green time at each intersection to minimize the expected bus delay travelling on exclusive bus lanes while taking the least green time from side-streets. Zeng et al. (2021) proposed a real-time CV TSP model including localized and route-based transit signal priority to minimize delay at intersections and routes and bus route schedule lateness.

To best of our knowledge, there is a lack of TSP strategies that consider minimizing total passenger travel time and the adverse impact on side streets under mixed traffic conditions. This study aims to fill this gap and develop an optimization-based TSP along with a delay prediction model to minimize average passenger delay at intersections.

2. The proposed solution approach

2.1 Assumptions

Three assumptions were made including: (*i*) the sequence of signal phases does not change, (*ii*) for each signal cycle, the arrival traffic flow rate is assumed to be constant, and (*iii*) a maximum of one TSP is granted within one signal cycle.

2.2 Problem definition

The most common performance measures for assessment of intersection signal control are average total delay, average total throughput, average total travel time, average passenger delay and average total number of vehicle stops (Eom and Kim, 2020). In this study, average passenger delay per cycle at an intersection was chosen to evaluate performance and optimise signal settings. A metaheuristic optimization algorithm is utilized to determine the optimal values for decision variables that would minimize this delay. The objective function is:

$$Min \sum_{k=1}^{K} \frac{\sum_{i=1}^{I} D_{i,k}(\alpha t_{GE}, \beta t_{BP}) * Occ_i + D_{b,k}(\alpha t_{GE}, \beta t_{BP}) * Occ_b}{\sum_{i=1}^{I} Occ_i + Occ_b}$$

Eq. 1: Objective function

where D_i and D_b are, respectively, the passenger car i and bus b delay, K is the total number of lanes, and I is the total number of passenger cars arriving at the intersection. t_{GE} and t_{BP} represent, respectively, the green extension period and inserted bus phase duration. α and β are coefficients assigned to decision variables t_{GE} and t_{BP}. Occ_i and Occ_b represent the passenger occupancy of private vehicles and buses, respectively. Constraints include:

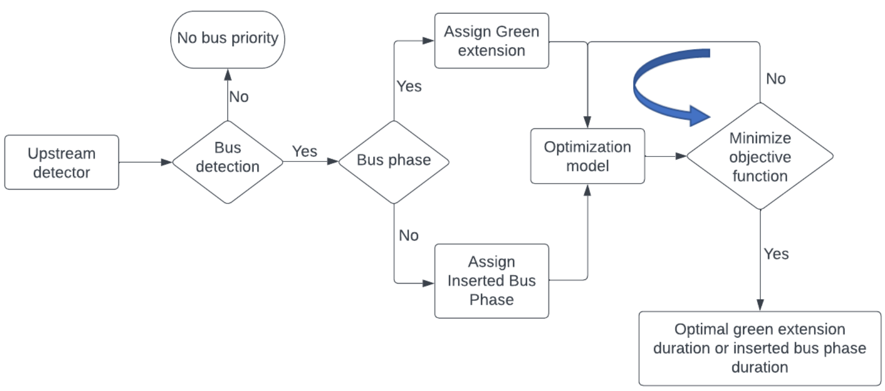
$$\alpha + \beta = 1$$
$$Minimum\ Green\ Extension \leq t_{GE} \leq Maximum\ Green\ Extension$$
$$Minimum\ Bus\ Phase\ Duration \leq t_{BP} \leq Maximum\ Bus\ Phase\ Duration$$

2.3 Solution algorithm

The TSP methodology proposed in this study comprises two actions that are green extension (GE) and inserted bus phase (BP). Separated detectors are placed 120m upstream from the stop-line to detect the presence of buses. For each signal cycle, only one TSP will be granted to an approaching bus. Figure 1 shows a flowchart for the proposed TSP. Upon detection of an approaching bus by the upstream detector, the TSP model evaluates the current state of the corresponding signal group. If the status of the signal group is green, the bus will be granted GE. Otherwise, a bus phase is inserted. Once the TSP has been determined, the optimal decision variable will be generated to minimize the proposed objective function.

As shown in the previous section, the delay estimation of passenger cars and buses are a function of t_{GE} and t_{BP}. To solve the above non-linear problem, a Harmony Search (HS) algorithm is proposed to find optimal green extension or duration of an inserted bus phase to minimize the average passenger delay at the intersection.

Figure 1: Flowchart of the proposed TSP



2.4 Lane-based delay prediction model

The methodology used to predict delay in this study contains two major steps including (i) to use shockwave theory to predict queue length for each lane within current signal cycle, and (ii) to estimate the bus delay ($D_{b,k}$) and passenger car delay ($D_{i,k}$) considering queue length.

2.4.1 Bus delay computation

A shockwave fundamental diagram is shown in Figure 2, where the delay experienced by a bus at an intersection on lane k during cycle n ($D_{B,k}^n$) can be calculated as the difference between the time a bus departs from the queue ($T_{BQ,k}^n$) and the time it joins the queue ($T_{BD,k}^n$).

$$D_{B,k}^n = T_{BQ,k}^n - T_{BD,k}^n$$

Eq. 2: Bus delay equation

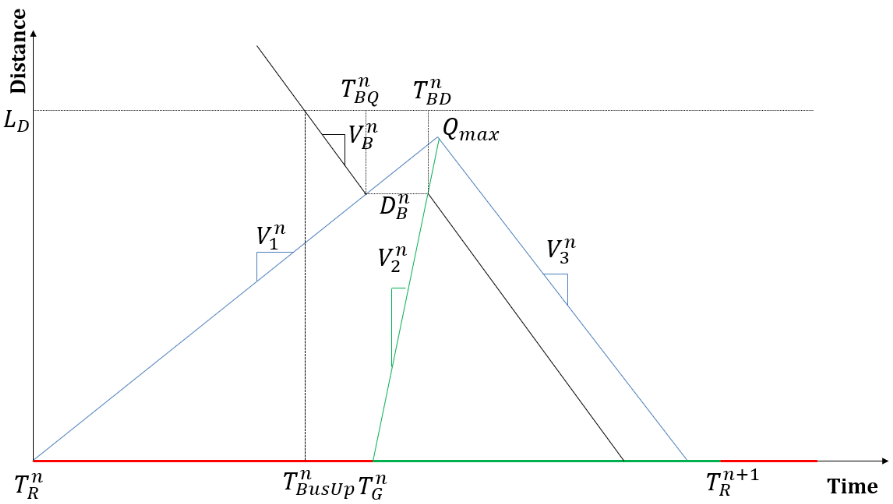
which can be extended as follows.

$$D_{B,k}^n = T_{G,k}^n + \frac{V_{B,k} * (L_{D,k} - (T_{BusUp}^n - T_{R,k}^n) * V_{1,k}^n)}{(V_{1,k}^n + V_{B,k}^n) * V_{2,k}^n} - T_{BusUp,k}^n - \frac{L_{D,k} - V_{1,k}^n * (T_{BusUp,k}^n - T_{R,k}^n)}{V_{1,k}^n + V_{B,k}^n}$$

Eq. 3: Bus delay computation

where n represents the n^{th} cycle, k represents the k^{th} lane, $T_{G,k}^n$ and $T_{R,k}^n$ are green and red start time, $L_{D,k}$ is the distance between upstream detector and stop line, $T_{BusUp,k}^n$ is the time when a bus passed an upstream detector, $V_{B,k}^n$ is bus speed passing upstream detector, $V_{1,k}^n$ and $V_{2,k}^n$ are the speed of queuing and discharge shockwave.

Figure 2: Bus delay computation shockwave diagram



2.4.2 Delay of general traffic

To estimate the delay of general traffic, it is necessary to consider two distinct scenarios. In the first scenario, the queue formed during red period cannot be fully dissipated during the following green phase, resulting a residual queue in subsequent cycles which is shown in Figure 3(b). In the second scenario, the queue formed during red period can be fully dissipated during next green phase, resulting no residual queue which is shown in Figure 3(a). Eqs. 4 and 5 represent the estimated delay for the first and second scenarios, respectively.

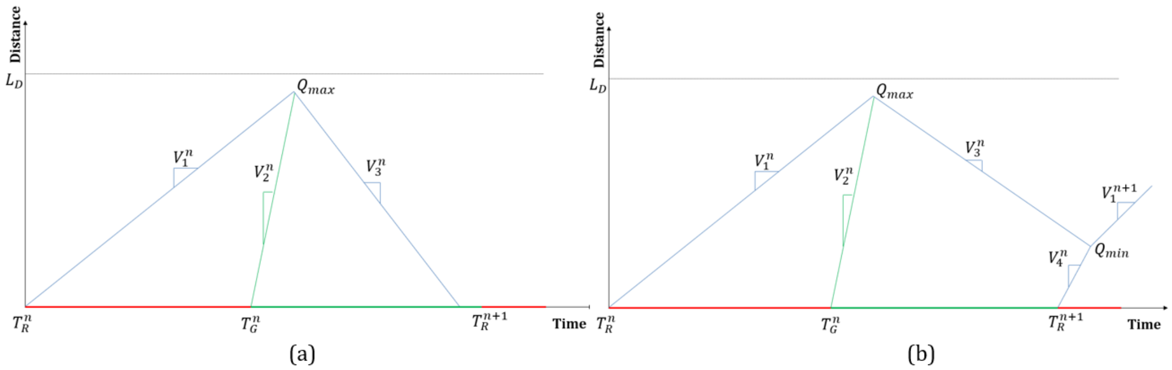
$$D_G^n = \frac{Q_{max}^n * (T_G^n - T_R^n)}{2} + \frac{Q_{max}^n * (T_R^n + \frac{V_2^n * (T_G^n - T_R^n)}{V_2^n - V_1^n} + \frac{Q_{max}^n}{V_3^n} - T_G^n)}{2} - \frac{Q_{min}^n * (T_R^n + \frac{V_2^n * (T_G^n - T_R^n)}{V_2^n - V_1^n} + \frac{Q_{max}^n}{V_3^n} - T_R^{n+1})}{2}$$

Eq. 4: Delay computation with residual queue

$$D_G^n = \frac{Q_{max}^n * (T_G^n - T_R^n)}{2} + \frac{Q_{max}^n * \left(T_R^n + \frac{V_2^n * (T_G^n - T_R^n)}{V_2^n - V_1^n} + \frac{Q_{max}^n}{V_3^n} - T_G^n\right)}{2}$$

Eq. 5: Delay computation without residual queue

Figure 3: Shockwave diagram at an intersection: (a) residual queue in next cycle, and (b) no residual queue in next cycle



3. Evaluations

The methodology outlined in the previous section was evaluated using a microscopic traffic flow simulation environment (Aimsun) including an isolated intersection along the Old Cleveland Rd corridor (Old Cleveland Rd & Creek Rd). The intersection is signalized with a phase-based control plan including four phases, and a cycle length of 140 seconds. The east-west approach has 60 seconds for go-straight movements and 15 seconds for right-turn movements, and north-south approach has 30 seconds for go-straight movement and 15 seconds for right-turn movements. The traffic demand is provided by Brisbane City Council, which is 2,254 vehicles for north-south approach (Creek Rd) and 3,350 vehicles for east-west approach (Old Cleveland Rd). The harmony memory size, maximum iteration, harmony memory consideration size (HMCR), and pitch adjustment rate (PAR) were set to 10, 50, 0.9, and 0.3, respectively.

To make simulation to be simplicity, some assumptions are made which are shown as follows:

- There is no bus-stop placed at intersection.
- For each signal control cycle, the upstream arrival traffic volume is at a constant rate.
- The bus and car passenger occupancy are set as 40 and 1.5 passengers each vehicle.

3.1 TSP strategies

Three different control strategies were compared including: (*i*) No TSP (NTSP) with a background signal timing plan and signal priority action; (*ii*) Unconditional rule-based TSP (URTSP) which assigned a green extension or inserted bus phase in response to the detection of a bus by upstream detectors. When a bus was detected during green split, the URTSP provided an extra 10 seconds of green time. Alternatively, if the bus was detected during red split, it assigned an inserted bus phase and terminate it once the bus passed a stop-line detector; and (*iii*) Optimization-based TSP (OTSP) which is the proposed control strategy as described in detail above.

Figure 4: Study site - Old Cleveland Rd & Creek Rd intersection

3.2 Simulation-based evaluation using Aimsun

The proposed TSP logic was developed in Python and the Aimsun Application Programming Interface (API) was utilized to enable the TSP logic within the Aimsun simulation platform. Table 1 presents the results of simulations conducted on three distinct control strategies. The average passenger delay and total travel time for both buses and cars are summarized in the table. It should be noted that all three scenarios were simulated under identical conditions of traffic demand and background signal control plan. According to the simulation results, the implementation of URTSP and OTSP lead to a considerable reduction in total travel time experienced by buses, when compared to the No TSP.

Table 1: Simulation based assessment of the TSP strategies

	Total passenger delay(hr)	Average passenger delay (sec/person)	Total travel time – Bus (hr)	Total travel time – Car (hr)
No TSP	152	62	0.35	151
URTSP	155(+2%)	63(+2%)	0.23(-34%)	155(+2%)
OTSP	147(-3%)	60(-3%)	0.3(-17%)	146(-3%)

4. Conclusions

This paper has proposed an optimisation-based bus priority strategy for isolated intersections. It seeks to minimize the average passenger delay at intersections. The main contributions of this study are shown as follows:

- A queuing mode used shockwave theory to describe bus and passenger car movements in a lane-based approach is proposed.
- An optimisation-based bus priority finding optimal signal timings of inserted bus phase duration and green extension duration to reduce minimize average passenger delay of car and bus is proposed.

A simulation-based experiment showed that the optimization TSP strategy gives a better performance regarding bus delay while minimize adverse impacts on other traffic compared to rule-based TSP. Future research is required to provide coordinated optimization-based TSP and to access travel time reliability through corridors. Future research is also required to study the impact of various levels of detection across the intersection and traffic corridor. Similarly, future research is required to relax or remove some of the assumptions mad in this study including capabilities to: (i) change the sequence of signal phases, (ii) consider variable arrival traffic flow rates, and (iii) consider multiple buses and the corresponding TSP strategies within one signal cycle if required.

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