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Impact of Transit Signal Priority on Level of Service at Signalized Intersections

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Abstract

The assessment of Transit Signal Priority (TSP) impacts at traffic signals is typically based on simulation and field studies. There is a need for macroscopic procedures for analysis of TSP as part of the Highway Capacity Manual (HCM) analysis methodology for signalized intersections. This capability will allow prediction of TSP impacts (and related control strategies) at a planning and operations level without the complexity of simulation modeling. The paper presents a technique of estimating the average green times for each lane group, and modifications to the HCM formula for estimating control delay in order to estimate the impact of TSP on the Level of Service (LOS) at each approach and the whole intersection. The technique uses readily available information on the frequency of the transit vehicles, TSP features (e.g., green extension, or red truncation), and also takes into consideration the additional delays because of the residual queues that are likely to occur on non priority approaches operating close to saturation. Application of the method at a signalized intersection with signal priority in the San Francisco Bay Area, and comparisons with simulated data show that the proposed methodology provides reasonable estimates of the TSP impacts, and it can be incorporated into the HCM analysis procedures for signalized intersections.

Keywords: transit signal priority; intersection capacity; level of service

1. Introduction

Transit Signal Priority (TSP) is a control strategy that has been increasingly used to improve transit operations in urban networks. The magnitude of the benefit obtained varies among networks that differ in their operating and transit characteristics (e.g., volume to capacity ratios for the different approaches, cycle lengths, transit frequencies) as well as their TSP features (e.g., minimum green extension, frequency of green extension versus red truncation). Several studies have shown that the implementation of TSP strategies can result to lower delays for priority transit vehicles and cars that travel in the same directions, but can have negative impacts on the delays of the cross (non-priority) streets. The magnitude of this negative impact varies from insignificant increases in their delays to major ones, mainly when the cross-streets operate close to saturation.

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This assessment of TSP strategies has been mainly based on simulation. Simulation studies are data-intensive and as a result, time consuming (Rakha and Zhang, 2004, Ahn and Rakha, 2006). In addition, most of them do not incorporate accurately the TSP logic and features, failing to realistically model the TSP systems. Another typical way of evaluating TSP strategies is through field tests (Ahn et al., 2005). In addition to their high costs (i.e., equipment, extra delays to traffic during the experiment) they are time consuming and depend on specific characteristics of the study site. Analytical models have also been proposed (Sunkari et al., 1995, Liu et al., 2008) which however, ignore random and oversaturation delays. As a result, they do not estimate accurately the impact in oversaturated conditions which is the case for non-priority approaches that operate close to saturation and can easily move to oversaturated operations once TSP strategies are introduced.

There is a need to develop methodologies that are able of estimating accurately and easily the impact that TSP strategies have on the delays of all vehicles traveling through the network in order to be able to evaluate in advance the benefits from implementing such strategies, before investing for them. The paper presents a technique of estimating the impact of TSP on the delays of all approaches and consequently, the LOS for each of those in a more macroscopic way. It uses readily available information on the TSP features and the distribution of transit arrivals to estimate the average green times for all phases. Then it uses that information along with the frequency of the buses to estimate the delays and the LOS for each of the approaches using the delay estimation formula and LOS thresholds of the HCM. The main advantage of this technique is that it is easy and accurate and does not require extensive data collection or calculations.

This paper is organized as follows: First, the methodology for estimating the average green times as a function of transit vehicle frequency and TSP characteristics, for each of the phases is presented. Next, this methodology is tested with data from a hypothetical intersection. Finally, simulated data from a real-world signalized intersection with signal priority in El Camino Real, in the San Francisco Bay Area, are used to compare the estimates of the TSP impacts obtained from the proposed methodology.

2. Average green time estimation

The average green time for all phases is estimated as a function of the distribution of the bus arrivals during a cycle as well as the TSP features (i.e., minimum and maximum extension and truncation). The estimation is based on the assumption of uniform arrivals during each signal cycle, meaning that there is equal probability of the bus arriving during any of the time intervals within a cycle. It is also assumed that the green time can be extended or advanced by fixed intervals of e and τ. The probability of that bus receiving priority treatment is equal to the probability of it arriving within the intervals of maximum length equal to e_{max} and τ_{max} before or after the initial phase extension respectively and it is:

$$\mathrm{P(Priority)} = \mathrm{P(Green\ extension)} + \mathrm{P(Early\ green)} = \frac{e_{max}}{C} + \frac{\tau_{max}}{C} \quad (1)$$

where:
e_{max}: maximum green extension allowed [sec]
τ_{max}: maximum red truncation allowed [sec]
C: cycle length [sec]

The expected value for green time for the priority phase given no priority is provided during that cycle, is equal to the initial green time allocated to it and it is:

$$\mathrm{E}[G_P|\mathrm{No\ priority}] = g_P \quad (2)$$

and if priority is provided it is:

$$\mathrm{E}[G_P|\mathrm{Priority}] = g_P + e \times \mathrm{P(Green\ extension} = e) + e_{max} \times \mathrm{P(Green\ extension} = e_{max}) + \tau \times \mathrm{P(Early\ green} = \tau) + \tau_{max} \times \mathrm{P(Early\ green} = \tau_{max}) = \frac{e^2}{C} + \frac{e \times e_{max}}{C} + \frac{\tau^2}{C} + \frac{\tau \times \tau_{max}}{C} \quad (3)$$

As a result, the expected green time for the priority phase given that there is a bus arriving during the cycle under consideration is:

$$\mathrm{E}(G_P|\mathrm{Bus}) = \mathrm{E}(G_P|\mathrm{No\ Priority})\mathrm{P}(\mathrm{No\ Priority}) + \mathrm{E}(G_P|\mathrm{Priority})\mathrm{P}(\mathrm{Priority}) \quad (4)$$

3. Impact of TSP on delays

Implementing TSP strategies does not affect negatively the main street which is served by the priority phases. It is likely that it will even benefit the priority approaches by the additional green due to TSP, depending on the progression characteristics on the arterial under consideration. However, TSP strategies have a significant impact on the delays of the non-priority phases, (i.e., cross-streets). The HCM formulas allow us to estimate that impact given that an estimate of the reduced green time for the cross-street can be obtained as described above. Knowing the green times for the priority approach allows us to estimate the average green time for the cross-street, given that a bus arrives during the signal cycle under consideration.

According to the HCM the control delay, *d*, for a lane group is given by the following formula:

$$d = d_1 + d_2 + d_3 \quad (5)$$

where:

d_1 is the uniform delay and it is calculated as:

$$d_1 = \frac{0.5C(1-\frac{g}{C})^2}{1-[\min(1,X)\,g/C]} \quad (6)$$

d_2 is the incremental delay and it is calculated as:

$$d_2 = 900T\left[(X-1) + \sqrt{(X-1)^2 + \frac{8kIX}{cT}}\right] \quad (7)$$

and d_3 is the initial queue delay at the beginning of the analysis period. In this study it is assumed that d_3 is zero.

c: capacity [veh/hr]
g: average green time [sec]
X: degree of saturation (=v/c)
v: volume [veh/hr]
T: duration of analysis period [hr]
k: incremental calibration delay factor
I: upstream filtering adjustment factor

A typical two-phase signalized intersection was used to obtain estimates of the impact that common TSP strategies have on the cross-street delays. The impacts were evaluated for several cycle lengths (*C*) and cross-street green time to cycle length ratios (*g*/*C*). The cross-street for this initial scenario had a flow ratio (*v*/*s*) of 0.33 which is indicative of an intersection operating well.

Figures 1 and 2 show the impact of two TSP strategies on the delays of the cross (no priority)-streets: 1) extension of the green time for the main street by 5 seconds (or equivalently truncation of the red time for the main arterial phase by 5 seconds), and 2) extension of the green time for the main street by 10 seconds.

As the Figures 1 and 2 indicate, the longer the cycle length, the lower the impact of the TSP strategies on cross-street traffic is. In addition, the higher the green time to cycle length ratio is, the lower the impact. This can be explained by the fact that the higher the green time to cycle length ratio for the cross street, the smaller the chance for the cross-street of operating close to saturation and forming residual queues that lead to significant increases in delay. In addition, the impact is much higher for higher reductions in the green time of the cross-street (i.e., longer extension or truncation intervals) as expected.

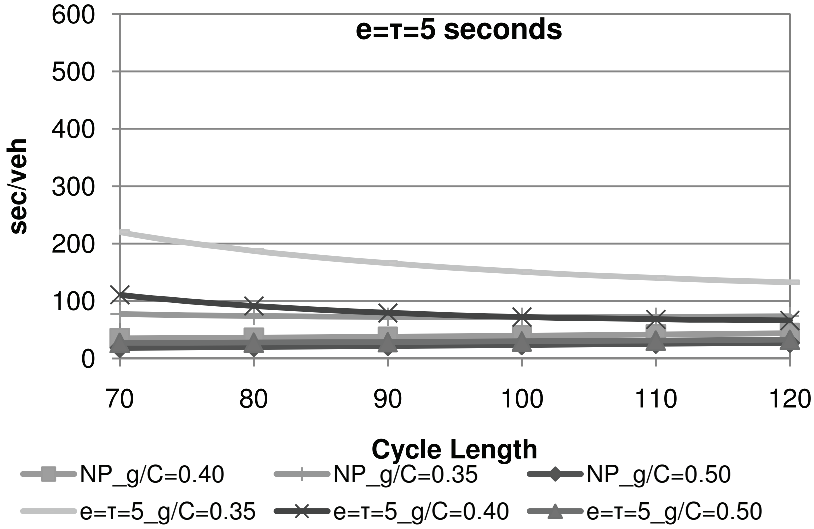

Figure 1: Impact of green extension/red truncation of 5 seconds on cross-street delays

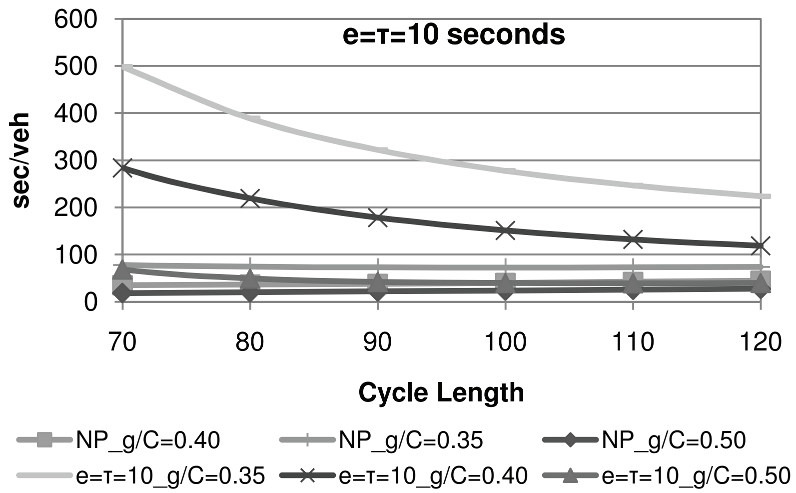

Figure 2: Impact of green extension/red truncation of 10 seconds on cross-street delays

Since the estimation of delay depends only on the values of volume to capacity ratios (degree of saturation, X) and green time to cycle length ratios (g/C) we are able to estimate factors which if multiplied with the delay experienced when no priority is provided, it can help estimate the impact of specific TSP strategies on the cross-street for each combination of X and g/C and for several cycle lengths. Since the value of X also depends on the green time provided, we are using the volume to saturation flow ratio (flow ratio, v/s) which is independent of the green times. The factor estimates for flow ratios of 0.14, 0.22, 0.33, and 0.42 and green time to cycle length ratios of 0.35, 0.40, and 0.50 are shown in the following tables. The use of such factors allows for quick estimation of delays and evaluation of TSP strategies without the need for intensive calculations or time-consuming simulations.

Table 1: HCM delay adjustment factors for v/s=0.14[1]

Cycle Length	g/C=0.35		g/C=0.40		g/C=0.50	
	e=τ=5sec	e=τ=10sec	e=τ=5sec	e=τ=10sec	e=τ=5sec	e=τ=10sec
70	1.28	2.03	1.27	1.66	1.29	1.64
80	1.23	1.63	1.20	1.48	1.25	1.62
90	1.20	1.48	1.20	1.43	1.22	1.48
100	1.17	1.40	1.18	1.38	1.20	1.42
110	1.15	1.34	1.16	1.34	1.18	1.38
120	1.14	1.30	1.14	1.30	1.17	1.35

[1]v~250 veh/hr/ln and s=1800 veh/hr/ln/g

Table 2: HCM delay adjustment factors for v/s=0.22[2]

Cycle Length	g/C=0.35		g/C=0.40		g/C=0.50	
	e=τ=5sec	e=τ=10sec	e=τ=5sec	e=τ=10sec	e=τ=5sec	e=τ=10sec
70	1.79	7.73	1.38	3.35	1.31	1.74
80	1.48	4.63	1.29	2.10	1.27	1.60
90	1.34	3.03	1.24	1.88	1.23	1.51
100	1.27	2.21	1.21	1.53	1.21	1.45
110	1.22	1.80	1.18	1.43	1.19	1.40
120	1.19	1.58	1.16	1.37	1.17	1.36

[2]v~400 veh/hr/ln and s=1800 veh/hr/ln/g

Table 3: HCM delay adjustment factors for v/s=0.33[3]

Cycle Length	g/C=0.35		g/C=0.40		g/C=0.50	
	e=τ=5sec	e=τ=10sec	e=τ=5sec	e=τ=10sec	e=τ=5sec	e=τ=10sec
70	2.84	6.43	3.14	8.06	1.48	3.73
80	2.53	5.25	2.52	6.04	1.37	2.46
90	2.29	4.44	2.09	4.71	1.30	1.93
100	2.10	3.85	1.81	3.80	1.25	1.69
110	1.94	3.40	1.62	3.15	1.22	1.55
120	1.81	3.04	1.49	2.68	1.20	1.47

[3]v~600 veh/hr/ln and s=1800 veh/hr/ln/g

Table 4: HCM delay adjustment factors for v/s=0.42[4]

Cycle Length	g/C=0.35		g/C=0.40		g/C=0.50	
	e=τ=5sec	e=τ=10sec	e=τ=5sec	e=τ=10sec	e=τ=5sec	e=τ=10sec
70	1.98	3.80	2.23	4.30	2.63	6.59
80	1.82	3.20	2.05	3.67	2.11	4.96
90	1.66	2.75	1.90	3.23	1.80	3.88
100	1.62	2.53	1.79	2.91	1.60	3.14
110	1.55	2.32	1.70	2.65	1.47	2.63
120	1.49	2.16	1.62	2.45	1.38	2.27

Assuming that the buses arrive on schedule, the probability of a bus with frequency $1/H$ arriving during one cycle of length C is:

$$\mathrm{P(Bus)} = \frac{C}{H} \tag{9}$$

4. Impact of TSP on level of service (LOS)

The impact of TSP strategies on the cross-street's LOS can be estimated by comparing the average delays of vehicles traveling on the cross-street with and without provision of TSP. Figure 3 illustrates the impact on the LOS of a cross-street for a 10 second provision of TSP (green extension or red truncation) to buses traveling on the main street with a frequency of 6 buses per hour. It can be seen from the figure that LOS for the non-priority cross street remains the same for provision of TSP for initial (without TSP) LOS A or B. The figure also reveals that for worse initial LOS, such as C and D, provision of priority to buss traveling on the main street can lead to much higher delays for the cross-street and can deteriorate their LOS by one level. A similar comparison of LOS for provision of 5 second TSP reveals that the LOS for the non-priority cross street on the average remains the same for initial LOS A, B, C or D but leads to higher level of service for initial LOS E. For a single cycle that priority is provided the impact on the LOS of the non-priority approach is much higher and the LOS can deteriorate by two levels for LOS C or higher.

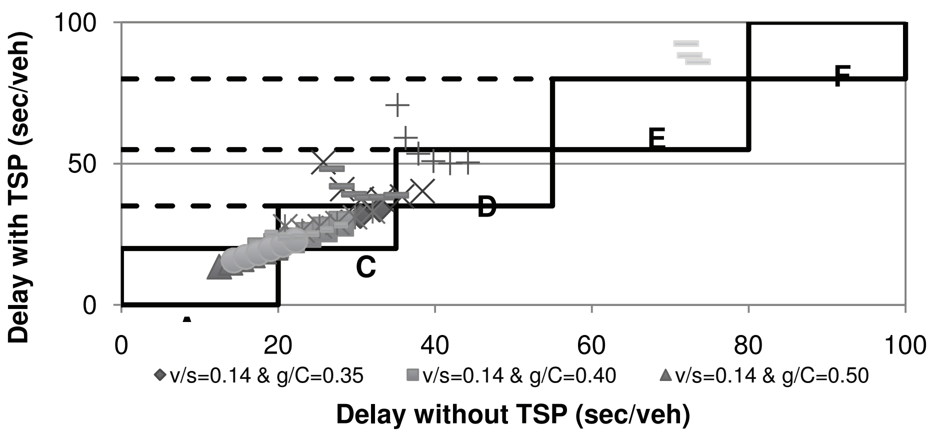

Figure 3: Impact of TSP of 10 seconds on cross-street LOS

5. Model Application

The model was validated with the use of simulated data from a real world signalized intersection in El Camino Real, in the San Francisco Bay Area. The intersection of El Camino Real and 25th Avenue, which is the intersection used for validation of the proposed model, is a four-phase signalized intersection that operated at a cycle length of 90 seconds. TSP is provided to buses traveling southbound on El Camino Real. The buses have a frequency of 10 minutes and priority can be provided at maximum once every two cycles. The maximum green extension is equal to the maximum red truncation and can be determined by the minimum green times allowed for all the other phases. The cross-street approaches have a flow ratio of 0.11 and a green time to cycle length ratio of 0.33. In order to facilitate the calculations, the assumption that TSP is provided at fixed intervals of 5 seconds, which is a common practice for TSP strategies, is also made.

The probability of that bus receiving priority treatment is equal to the probability of it arriving within the extension or truncation interval allowed is:

$$\mathrm{P(Priority)} = \mathrm{P(Green\ extension)} + \mathrm{P(Early\ green)} = \frac{26}{90} + \frac{26}{90} = 0.58$$

The expected value for green time for the priority phase given no priority is provided is:

$$\mathrm{E}[G_P|\mathrm{No\ priority}] = 30\ \mathrm{seconds}$$

and if priority is provided it is:

$$\mathrm{E}[G_P|\mathrm{Priority}] = 30 + 2 \times \frac{5}{90} \times (5 + 10 + 15 + 20 + 25) = 38.33\ \mathrm{seconds}$$

because there is a 5/90 priority for a bus to arrive at any of those 5 intervals that could provide priority of 5, 10, 15, 20, and 25 seconds. As a result, the expected green time for the priority phase given that there is a bus arriving during the cycle under consideration is:

$$\mathrm{E}(G_P|\mathrm{Bus}) = 30 \times (1 - 0.58) + 38.33 \times 0.58 = 34.83\ \mathrm{seconds}$$

which means that the green time for the priority phase would have been extended by 5 seconds.

According to the simulation runs performed by Liu et al. (2004), the average delay of vehicles at the intersection is 12.4 sec/veh for the through movements on El Camino and 34.8 sec/veh for all movements on the cross street. The HCM formulas estimate a delay of 14.0 sec/veh for the through movements and 36.62 sec/veh for all movements on the cross street. Using the factor for a flow ratio of 0.11 and a green time to cycle length ratio of 0.42 as shown in Table 1 we are expecting a delay of 43.9 sec/veh for those cycles that have a bus arriving. Since not all cycles have buses arriving an average value for the cross street could be obtained if we take into account the frequency of the buses. So over an hour, the average delay per vehicle on the cross street can be estimated as follows:

$$d = \mathrm{E}(d|\mathrm{Bus})\mathrm{P(Bus)} + \mathrm{E}(d|\mathrm{No\ bus})\mathrm{P(No\ Bus)} = 43.9 \times 0.15 + 36.6 \times (1 - 0.15) = 37.7\ \mathrm{sec/veh}$$

The delay obtained from simulation under the same traffic conditions and TSP strategies is 39 sec/veh. This indicates that there is only a 3% between the delay estimated here and the delay obtained from simulation. This average over an hour delay indicates that the specific TSP strategies add only a 3% of delay to the cross-street. In addition, it indicates that the LOS for the cross-street does not change, but it remains in level D for the conditions under consideration.

6. Discussion

A method for estimating the impacts of transit signal priority (TSP) at signalized intersections using the HCM procedures is proposed. The method uses information commonly available on traffic conditions (v/s), signal settings (g/C), frequency of the buses and the TSP strategy characteristics (green extension/red truncation intervals). The method provides adjustment factors for estimating the delay under TSP from the HCM estimated delay under normal operating conditions.

Comparisons of control delays for the non-priority intersection approaches under TSP and normal signal operations show that the LOS remains the same under low to medium flow conditions (initial LOS A through C). Under high flow conditions, provision of TSP can deteriorate the LOS on cross-streets by up to two levels (e.g., from LOS C to LOS E). These results depend on the TSP features and the frequency of transit vehicles.

Application of the proposed methodology on a real-world signalized intersection with recently implemented signal priority on El Camino Real, in San Francisco Bay Area, and comparisons with simulated data show that the proposed methodology provides reasonable estimates of the TSP impacts, and it can be incorporated into the HCM procedures for signalized intersections.

The work described represents the findings to-date of work in progress. Ongoing work includes the analysis of field data on approach/movement delays under normal and TSP conditions along recently implemented transit signal priority projects in San Francisco Bay Area and San Diego. Data on operating conditions are continually collected as part of the PATH Traffic and Transit Laboratory (Zhang et al., 2010).

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