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Transit Signal Priority in Smart Cities

Bahman Moghimi and Camille Kamga

Abstract

Giving priority to public transport vehicles at traffic signals is one of the traffic management strategies deployed at emerging smart cities to increase the quality of service for public transit users. It is a key to breaking the vicious cycle of congestion that threatens to bring cities into gridlock. In that cycle, increasing private traffic makes public transport become slower, less reliable, and less attractive. This results in deteriorated transit speed and reliability and induces more people to leave public transit in favor of the private cars, which create more traffic congestion, generate emissions, and increase energy consumption. Prioritizing public transit would break the vicious cycle and make it a more attractive mode as traffic demand and urban networks grow. A traditional way of protecting public transit from congestion is to move it either underground or above ground, as in the form of a metro/subway or air rail or create a dedicated lane as in the form of bus lane or light rail transit (LRT). However, due to the enormous capital expense involved or the lack of right-of-way, these solutions are often limited to few travel corridors or where money is not an issue. An alternative to prioritizing space to transit is to prioritize transit through time in the form of Transit Signal Priority (TSP). Noteworthy, transit and specifically bus schedules are known to be unstable and can be thrown off their schedule with even small changes in traffic or dwell time. At the same time, transit service reliability is an important factor for passengers and transit agencies. Less variability in transit travel time will need less slack or layover time. Thus, transit schedulers are interested in reducing transit travel time and its variability. One way to reach this goal is through an active intervention like TSP. In this chapter a comprehensive review of transit signal priority models is presented. The studies are classified into different categories which are: signal priority and different control systems, passive versus active priority, predictive transit signal priority, priority with connected vehicles, multi-modal signal priority models, and other practical considerations.

Keywords: transit signal priority, traffic system communication, adaptive control, connected vehicles, smart cities

1. Introduction

Transit-Oriented Development (TOD) has been widely considered as a wise approach to make the public transit more attractive. Transit Signal Priority (TSP) is a promising and key tool in support of TOD strategies. The first research about TSP dates back to the 1970s [1]. TSP has evolved, together with its application tested and implemented through the advances in intelligent transportation technologies. TSP is an operational treatment that facilitates the movement of public transit,

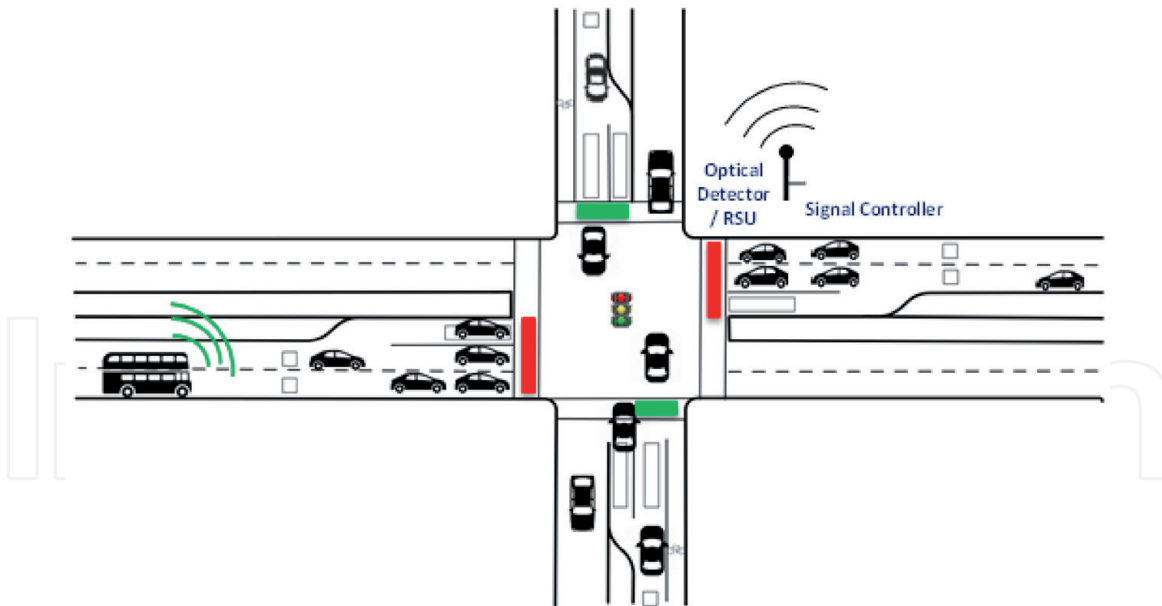


Figure 1.
Transit signal priority framework.

either busses, tramways, or streetcars, through signalized intersections without the interruption of red signal lights when possible (see **Figure 1**). It can be an effective strategy for lowering transit vehicle delays at signalized intersections as well as passengers delays, reducing fuel consumption and vehicle emissions, preventing bus-bunching, and significantly enhancing transit reliability which results in transit with lower passenger waiting time and operating costs (smaller transit fleet size).

The Transit Capacity and Quality of Service Manual [2] described bus preferential treatments at intersections including transit signal priority, queue jumping, curb extension, and boarding islands. Among the stated transit treatments, TSP has the lowest cost and can easily be implemented in dense urban transportation networks, while other treatments require more capital and physical spaces to be considered. In practice, transit agencies are more interested in making use of limited resources in an efficient manner and TSP could satisfy such needs. However, the impact of TSP will prove more effective with the use of extensive evaluation, ongoing performance monitoring, and adjustment after the initial implementation [3]. By 2015 [4], 109 cities around the world, mostly in North America and Europe, have implemented TSP. However, the majority of attempts used simple and easy-to-implement logics in practice. Portland, Los Angeles, Chicago, and New York City in the United States have been the pioneer cities in implementing TSP in order to enhance their transit system. Various technologies have been deployed for TSP including: the Loopcom System in Los Angeles, CA, the Amtech System in Seattle, WA, the TriMet in Portland, OR, and wireless local area network in Minnesota, MN and in New York City, NY [5–7].

2. Transit signal priority tactics

The goal of all tactics is to grant green time when transit vehicles are approaching intersections, which would offer them shorter delays. To do so, a combination of TSP tactics is given the best result. Thus far, a lot of tactics have been used; most of them are listed below.

Green Extension is one of the main TSP tactics that has been used in most TSP studies. It extends the green time when the transit vehicle is expected to arrive a

few seconds after the end of green time, which opens a short green-window for the transit vehicle. It provides a relatively large bus delay-reduction, but only for a small fraction of busses that arrive at the signals approximately the end of green phase [8, 9]. The maximum green extension is an input value in the TSP logic. Based on that, and together with bus speed, a maximum point/time at which transit can be detected will be measured [10].

Early Red or Green Truncation is another main TSP tactic scheme that has been widely implemented. It is granted to accommodate transit vehicle that would arrive a few seconds before the start of green. Green truncation cuts down the green time of the conflicting or non-transit phases so that the signal cycles faster and provides a green window sooner to the transit vehicle that stopped behind the traffic lights. This tactic serves all busses caught at red light, providing a small benefit to many [8, 9]. Since the early red technique cuts down the green of the conflicting phases, while there are vehicles in the queue, it causes greater disruption to the conflicting traffic and it is recommended to be applied to intersections with low to medium interruptible bus requests.

Phase Rotation is a TSP technique that has been recently emerged in studies. It changes the sequence of the phases in the ring barrier signal system to match the bus's arrival time with the green light. It mostly changes a leading left phase to a lagging left phase or vice versa. Thus, the application of phase rotation tactic comes into play when there is a left-turn phase in the ring barrier with more than two critical phases. For example, it assumes that the initial signal timing design is set to be leading left and lagging through. Assuming that the bus runs in the through-phase, the phase rotation tactic changes the sequence of the phase in such a way as to make the through-phase lead and the left-turn phase lagged. The effect of phase rotation is ineffective where bus volume is high [9].

Phase Insertion is another tactic used to provide green time for transit vehicles. This tactic strategy is applied mostly when there are several turning movement phases, and the logic is not flexible enough to handle such a case when the transit vehicle arrives in the middle of a red light, making the logic unable to apply other TSP techniques like Green Extension or Early Green. Instead, it creates a temporary green phase within a cycle. Sometimes it is called Double Realization because the transit-phase receives green time twice in one cycle. Double realization is used for a left-turn phase at an intersection with high bus requests [9]. The phase sequence used was leading left - through movement - lagging left (for the second time), which all were applied in one cycle, at a signalized intersection near a major bus terminal [9].

Queue Jump is another transit preferential treatment that stretches a short bus-lane at traffic signals, together with a specific queue jumper leading phase interval. This allows busses to receive green light sooner in order to be ahead of the queues backed-up in the adjacent lanes [11]. Queue jump was applied in a few studies and the results have shown that the combination of queue jump treatment and signal priority tactics have yielded the highest benefit in terms of transit travel time, speed, and delay as compared to scenarios in which each one is deployed separately [12, 13]. Cesme and Altun [14] studied the effect of queue jump lane on a hypothetical intersection. The results revealed that a queue jump lane corresponding to the 95th percentile queue has reduced the transit delay 1.3 times more than that of queues measured by the 35th percentile.

There are other transit signal tactics that have been introduced, which in a sense is the combination of the above listed tactics; some of which include: transit phase truncation and queue dissipation [15], early red, flush-and-return [16], expedited return [17, 18], etc.

3. Signal control systems and TSP

To better understand how to treat transit differently, diverse types of signal control systems need to be explained. Traffic signal system is one of the most significant parts of transit signal priority application in the emerging system of smart cities. Signals have been designed to control demand so as to improve traffic flow. There have been many developments in signal control systems. In this section, signal control models are categorized into four generations including: fixed time, coordinated-actuated, fully actuated, and adaptive signal control.

Pre-timed (fixed) signal control means that each phase has a fixed split length, resulting in a signal with a fixed cycle length. To be more responsive to traffic changes, one approach could be to use different plans according to the time of day (a.m. and p.m. peak, midday, nighttime, etc.). This way, the historical traffic demands will be used to determine signal timing plans.

The TSP on the fixed time control logic indicates whether the transit is projected to pass through the signal at a green light. If so, no alternative is made; but if the bus is projected to be at the stop line just after the end of green, green extension tactic will extend the green time until the transit vehicle can pass through or before the allowable maximum green. The green time required for an extension is taken from the next phase or other conflicting phases (if there are more than two critical phases). However, if the bus is at the signal while traffic from another approach is being served, the TSP logic truncates the active green phase, after the minimum green of that phase is satisfied. In the fixed-time control logic, applying TSP will reduce bus delay substantially, whereas it may increase the delay of the conflicting phases. Lack of compensation in the fixed time signal control does not allow it to recover from interruptions like TSP. That is part of the reason why many developed models have limited applying TSP over the fixed-time control at every cycle [17].

Coordinated-actuated signal control is another controlling system that is mostly being used for signals placed along a corridor. The logic provides all signals with a fixed cycle length and let non-coordinated phases behave like actuated control, aiming to enlarge green bandwidths and allow all slacks to run in the coordinated phases. Cycle length, force-off points, offsets, and phase sequences are mostly the signal timing parameters that are being optimized widely through available signal optimization software like Synchro and Transit-7F Error! Reference source not found.. There have been some optimization models developed over coordinated-actuated control to make its performance even better which can be found in [19, 20].

Applying TSP to coordinated-actuated logic is done by granting green extension to the coordinated/transit phase, early green to the actuated phases (non-coordinated phases), and TSP phase rotation whenever it is needed. As the cycle length is fixed, like the fixed-time control, the granted green extension time is taken from other conflicting phases. Actuated control with absolute priority can result in near zero delay for busses, but it sometimes causes long delays for the general traffic [21].

Actuated signal control relies on traffic data from sensors embedded in the infrastructure including loop-detectors, video detectors, or radar, to make controlling decisions. Actuated control better captures the real-time dynamic of traffic system since traffic demand may fluctuate from time to time. The fully actuated signal control run as fast (snappy) as possible to have less slack time, cycle length, and thereby less overall delay at intersections [22]. It matches supply to demand in real time. It has a feature of compensation which means if the controller gives more green time to a phase due to considerations such as TSP; the logic automatically will compensate and provide more green time to the conflicting phases in the next cycle. The faster it runs, the more efficient it will be [23–25]. The actuated traffic signal

functions approximately as a fixed signal when the degree of saturation is too high (oversaturated condition).

Adaptive signal control gets feedback from detectors based on the latest update of the past 5 or 10 minutes to update and re-optimize the control plans. Adaptive control can also be designed to predict traffic flow and optimize in the anticipation of the flows expected to arrive in the next few minutes (e.g. 2 to 5 min horizon). There are several adaptive control systems being developed; some of which include: SCATS [26], OPAC [27], TRANSYT-7F [28], UTOPIA [29], SCOOT [30], RHODES [31], ACS-Lite [32], MOTION [33], and more programs are also coming on to the market. Many of them are adaptive signal systems with a centralized controller. In adaptive signals with centralized control, the complexity increases as the number of traffic lights and contributing variables increase. Adaptive control with decentralized approach has also been developed, e.g. self-organizing system, that functioned well with signal priority [18].

The use of TSP on top of adaptive signal control was developed by many scholars. TSP applied to SCATS includes green extension, special phase sequences, and compensation to the non-transit phases [34]. Transit priority on TRANSYT-7F benefited bus delay-saving by 6 s/intersection/bus [35]. TSP on UTOPIA reported a 20 percent increase in the average bus speeds [36]. TSP with SCOOT reached bus delay-savings ranging from 5 to 10 s/signal [35]. Priority on RHODES has also increased traffic speed and reduced average and variance of bus-delay significantly [37, 38]. TSP with self-organizing system result in a very low bus delay [18, 39].

4. Passive versus active

Passive or inactive TSP refers to an initial method of signal priority which adjusts the signal timing offline while relying on the historical data. This adjustment mainly changes signal time parameters including split length, offset, and cycle length. The objective of signal setting with respect to passive TSP is to increase the probability of transit vehicles arriving at the intersection during the green interval. However, passive TSP is inflexible in adapting to the dynamic flow of traffic and bus conditions. The reason is that passive priority always provides a green light to transit even if there is no transit vehicle; not to mention about the delay it would cause to the other conflicting phases by giving ineffective green to the bus-phases. Passive priority becomes more effective when the traffic volume is light or moderate, with high transit frequencies, and predictable transit travel time [40]. Passive priority is cheap and easy-to-implement; both are advantages, since the transit detection and communication equipment are not required. It is worth noting here that preemption priority applies priority tactics abruptly. This is sometimes done by interrupting signal operation by skipping phases or terminating pedestrian clearance time, in order to permit a specific vehicle (e.g. ambulance) pass through the traffic light. Preemption can be considered as the highest level of priority, which is frequently used for emergency vehicles [41].

Contrary to passive priority, active TSP is about granting priority tactics in real time and only to those transit vehicles that are present or about to approach the signalized intersections. In an active priority system, the real-time information regarding transit vehicles' speed and location should be detected. Some standard vehicle/bus detection techniques are inductive loops, infrared, and radio based systems which are considered as static detection or selective vehicle detection (SVD) [42, 43]. On the other hand, the automatic vehicle location (AVL) system is another transit detection approach that provides dynamic monitoring of transit location. Taking into account the use of detectors, TSP logic is activated when the transit

vehicle passes the check-in detector, which is located upstream of the signal. Where to put the check-in detector is not deterministic and its optimal location is mostly related to traffic demand, and signal timing. The result demonstrated that putting a detector between 450 ft. (150 m) and 900 ft. (300 m) upstream of the intersection can output better results [43]. Meanwhile, the detection should cancel out the priority request when transit passes the stop-line detectors (check-out detectors). Those are located just after the traffic light, indicating the transit vehicle received priority, could pass through, and it is the time to start compensating the amount of time taken from the conflicting phases. Active TSP has been demonstrated as a better approach to improve transit performance, to better accommodate uncertain arrival time, and make on-street transit more reliable, faster, and cost-effective [42, 44]. Active TSP has been taken into consideration worldwide. For instance, applying active signal priority was studied on the two old and large street-car systems in Melbourne, Australia, and Toronto, Canada [45]. The results confirmed that such an approach is a cost-effective approach to manage traffic systems.

Song et al. [46] compared the GPS-based TSP and traditional TSP on two corridors in Utah, and it was found that GPS-based TSP reduced the same delay and travel time similarly to the traditional TSP. Surprisingly, the GPS-based signal priority system was effective in the flexible detection zone and could bring conditional priority into its logic while causing smaller impact on the side-street traffic. Active priority has recently focused its attention not only on the presence of transit vehicles, but rather on applying priority logic based on some conditions.

Unconditional priority means granting TSP tactics to the upcoming transit vehicles regardless of cross-street traffic or queue length, state of signal, or transit arrival time. It is more of an aggressive approach toward granting priority. In other words, unconditional priority is beneficial in improving bus delays, travel time, and reliability when the bus frequency is low, and when the traffic demand over signal is low. On the other hand, conditional priority grants transit signal priority only if the state of signal and bus arrival meet some defined requirements. For instance, conditional TSP can be applied if some of the following criteria are met: transit is behind schedule (e.g. let us say 5 min behind as being late), transit passenger-occupancy is more than a defined threshold, the intersection is under saturated level, no queue spillback is happening, the signal did not have a priority request in the previous cycle, etc. It is more complicated than the unconditional priority because it needs more updated information about transit and intersections. Conditional priority will improve bus headway irregularity, crowding, and mean running time to almost the same levels as what absolute TSP. More importantly, conditional TSP makes transit running time less varied (less standard deviation of running time), which indeed improves the reliability of transit scheduling service. The performance of conditional TSP was studied and found that it is more effective for bus routes experiencing more severe lateness [47–49]. Meanwhile, person-based signal priority approach has been recently introduced optimizes signals and applies conditional transit priority based on transit and vehicle passenger-occupancy conditions [50].

5. Transit arrival consideration

Predictive transit priority approaches give more flexibility to the controlling logic to enlarge the scope of signal timing to adjust itself more ahead of the transit arrival time and makes less adverse impact on the conflicting traffic. An accurate transit prediction can be a hint to passengers' departure time from point to point, so as to create more successful transfers at stops. It helps transit agencies to control and monitor their systems with more responsiveness through real time dispatching and

scheduling, and making the transportation system a more resilient one. However, there are many parameters involved in the prediction of transit travel time, some of which are listed by [51] including: stochastic traffic flow uncertainties along the route, queue length in front of a traffic light, route length, uncertainties in dwell time (caused by the variation of passengers getting on and off at bus stops), weather conditions, times of day, statistical fluctuation in historical data (with large standard deviation), and GPS data error.

Uncertainty in transit running time and dwell time is mostly pronounced and has been conducted by many scholars who have been developing predictive transit arrival models. Bus dwell time itself consists of passenger boarding and alighting time, door opening and closing time, and clearance time. Hence, predicting the dwell time is cumbersome and a good prediction of transit dwell time, specifically when there is a nearside bus stop, increases the precision of transit arrival time at the target intersection. One of the primary studies about dwell time prediction at nearside bus stops was presented by Kim and Rilett [52]. They used a regression model to come up with an upper and lower bound for dwell time with respect to the bus load, headway, and schedule adherence. Such prediction was included in the improved TSP algorithm which then was applied over a fixed-time signal control. It benefited the operation of bus systems well. Lee et al. [15] developed a predictive model for dwell time at a nearside bus stop, based on headway and passenger arrival rate. Ekeila et al. [53] presented a linear regression and applied empirical Bayesian and Kalman filtering refinement to improve the prediction performance. The developed model, applied to LRT's arrival time (including running time and dwell time) to predict its boundary length, was one standard deviation from its arrival time.

Some researchers have attempted to predict the transit arrival time further ahead of the target signalized intersection. Their focuses were mostly on the prediction of the transit travel time (running time) together with the dwell time consideration. Zlatokovic et al. [54] developed predictive priority for LRT in Salt Lake City, Utah which could reduce train travel time by 20–30%. The logic used almost all TSP tactics along with peer-to-peer communication between intersections. With the peer-to-peer communications, the logic activated priority when the train was stopped at the adjacent intersection, pointing to the target intersection to be prepared for the arriving train. Wadjas and Furth [55] used advanced detectors in order to detect the light-rail's arrival more ahead of the target intersection. Once the transit is detected, the logic applies the cycle length adaptation which lengthens or shortens the cycles/phases in such a way as to find the best match aligned with the TSP tactics. The logic applied to the signals with the fully actuated control. They found that the logic functioned better in enhancing transit travel time and regularity compared to the simple preemption, with a negligible impact on general vehicular traffic and pedestrians. Moghimi et al. [18] developed a model that calculates the expected remaining dwell time, added to the adaptive bus running time estimation, at each time-step of the simulation in order to predict the bus arrival time. Their presented model reduced bus net delay to less than 5 seconds per intersection. Moghimi et al. [56] also developed a look-ahead TSP to include a longer range of prediction in order to provide transit priority far in advanced. Their presented model outperformed the conventional TSP model and improved the reliability of travel time significantly.

6. Signal priority with connected vehicles

Some of the advanced TSPs are based on the wireless communications using Global Positioning System (GPS). These systems only report instantaneous

vehicle location data. Also, with the advances in emerging technologies, vehicles can communicate with each other (V2V) and with the infrastructure (V2I), through 5.9 GHz dedicated short-range communication (DSRC). Using this technology, each vehicle is equipped with an on-board unit (OBU) that broadcasts the vehicle speed, and acceleration at 10 times a second. A road side unit (RSU) is installed at the intersection to broadcast traffic signal status and also intersection geometry maps. The RSU can receive messages from surrounding vehicles and can provide better traffic resolution.

As soon as a transit vehicle enters the Dedicated Short-Range Communication (DSRC) range of intersection, it receives the map of the intersection and determines its location. Then, it broadcasts a request message and asks for priority. The RSU at the intersection receives the request and provides treatment. If the vehicle's speed changes dramatically, (e.g. the vehicle joins a queue) or if the transit vehicle stops at the bus stop, an updated request is broadcasted. The updated request is received by RSU and proper actions are planned. Connected vehicle technology can provide countable data because it updates vehicle dynamical traffic-related information like speed, acceleration, location, and other vehicle data in real time [57]. Such technology also provides the information about passenger counts (sitting/standing on transit) and at stops which can be transmitted to the signal controller in real time which makes dwell time prediction more accurate.

Hu et al. [5] used TSP with connected vehicles (TSP-CV) technology and compared their logic with conventional TSP and no-TSP scenarios. Results reported that the proposed logic reduced bus delay between 9–84% as compared to conventional TSP, as well as outperforming the no-TSP scenario. Meanwhile, it was shown that as volume-to-capacity ration increases (approaching to v/c equal to 1), the difference between TSP using connected vehicle and conventional TSP decreases. Hu et al. [58] continued their studies on conditional TSP-CV and proposed a person-based optimization method along with recommending a desired speed to the bus. The conditional logic was applied only to busses that are behind schedule and it was tested on two closely spaced intersections with fixed-time control. The results revealed that conditional TSP-CV performed better, specifically when the v/c is under saturated, and again it was found that as demand increases, when it approaches capacity, the benefit of TSP decreases. Lee et al. [59] tested the application of TSP in connected vehicle technology over a smart road test bed in Blacksburg, Virginia. The experiment results confirmed that the TSP-CV logic provided bus green extension with a 100% success rate, together with reducing bus delay between 32 to 75% as compared to No TSP scenario.

7. Multimodal traffic signal

In transportation systems, there are many users at signalized intersections that consist of passenger cars, commercial vehicles, busses, streetcars, emergency vehicles, snowplows, bikes, and pedestrians. The idea of providing TSP is not just to prioritize public transit but making other modes of transportation remain relevant in any developed TSP system. The conventional traffic controlling system treats all vehicles of different class/mode as an aggregate flow of traffic into a signal flow. This approach does not adequately consider each mode based on weight per se and is not well-aligned with the system operating objective [60]. On the other hand, treating each mode separately would result in a sub-optimal system performance [61]. The better manner of treatment is to come up with an algorithm that can consider all traffic modes based on their weight in order to reach the overall objective function. Recently, many new researchers have been developing algorithms that

can better quantify such objective function including all modes and then make the TSP algorithm more holistic.

He et al. [62] formulated a mixed integer linear program (MILP) for robust multiple priority requests with different modes including busses, pedestrians, and cars. The mixed-integer nonlinear program was used by Christofa and Skabardonis [63] to minimize total person delays, while assigning priority to transit based on the passenger occupancy. It is true that at one signalized intersection, pedestrian is a dominant mode, at another one, bus or truck is a dominant mode. Hence, a better approach would be to make the signals friendly with respect to the relative importance of each signal. Zamanipour et al. [64] developed a new approach that capture a relative importance of each section of the traffic signal and then establish a priority policy for that. They enhanced the work done by [62] and used such a flexible implementation algorithm that considers real time actuation on top of the MILP [60]. The developed model was designed to be utilized under a connected vehicle environment and was tested in San Mateo, California and Anthem, Arizona to confirm the better performance of the multimodal control over the fully actuated control. Later, Beak et al. [65] improved the MILP model to consider peer-to-peer signal priority control in a corridor. They designed a signal priority control framework to address the limitation of the effective range of DSRC and the extent of the intersection map message.

In today's complex transit network, multiple priority requests at intersections occur frequently. Although applying a first-come-first-serve policy is a widely acceptable approach in many cities, it cannot be the best option and sometimes can perform worse compared to providing no priority [66]. Therefore, some scholars tried to challenge this approach and take better advantage of priority logic to make it more beneficial in terms of minimizing total transit delay. Head et al. [67] developed a mixed integer programming for multiple-priority requests problems based on a precedence graph. Their findings demonstrated that their model performed better in minimizing total priority delay compared to the first-come-first-serve policy. He et al. [68] developed a fast heuristic algorithm to provide priority to simultaneous multiple requests in real time using V2I communication. Ma and Bai [69] proposed a decision tree for optimizing TSP-requests sequence. Ma et al. [70] used a dynamic programming model to generate an optimal sequence for the conflicting requests.

8. Other practical considerations

Another approach being mentioned in the literature relates to providing facilities with exclusive or dedicated bus lanes and giving transits/busses exclusive right of way. The advantage of dedicated/dedicated bus lanes is to free busses from traffic interference and benefit transit operation. However, taking a lane from general traffic and assigning it to transit may increase general traffic travel time, specifically when congestion is high [71, 72]. Eicher and Daganzo [73] proposed a bus lane with intermittent priority which allows general traffic to use the dedicated bus lane dynamically when it is not used by busses. Their idea is applicable on bus route with low frequencies. Indeed, TSP associated with exclusive bus lane [13, 74] and TSP with intermittent priority [75] revealed improvement in bus travel time and its reliability. An example of a transit system with dedicated lane is bus rapid transit (BRT), which is an integrated system of facilities that plays a significant role in today's urban transportation and can reasonably improve bus speed, travel time, reliability, as well as serving as a catalyst for redevelopment [76]. TSP with BRT can produce significant enhancement, because in such a system, TSP can be applied to any time without being worried about queue length ahead of the transit [77]. In addition, simulation results demonstrate that applying TSP with BRT was the most

effective scenario in reducing travel times (up to 26%) and delays (up to 64%), as well as increasing bus speed (up to 47%), when it was compared to scenarios without TSP and BRT [78].

The location of bus stops along the corridor is frequently under discussion and their placement depends on the traffic demand, geometry, and policy constraints. Bus stop locations can be far-side, near-side, or mid-block. With regard to the stop setback, the near-side bus stop can change into midblock or far-side bus stop as the setback distance increases. A far-side bus stop is mostly better than a near-side bus stop [14, 79, 80]. It can either cause a very low delay or zero net-delay, whereas a near-side bus stop can reduce a delay in a few cases like reserved bus lane, but it will cause increased bus delay depending on factors like cycle length, red ratio, dwell time, and stop setback distance [79]. Cesme et al. [14] compared three main transit preferential treatments including queue jump lane, transit signal priority, and stop location evaluation over an isolated test-intersection with a fixed cycle length, and bus headway of six minutes. After extensive simulation runs under various scenarios, the results indicated that relocating the bus stop from near-side to far-side resulted in the most delay-reduction per intersection when it was compared to the two other scenarios. Results showed that a far-side bus stop was superior to the near-side one with zero setback distance. Far-side relocation's delay-saving became smaller as the dwell time at the near-side stop increased. This can be interpreted as the signal's red time and dwell time have a lot of overlap. Bus delay with near-side stops can be reduced by lowering vehicular queue interaction through increasing setback distance or decreasing signal cycle length [14, 80].

9. Summary

In this chapter a comprehensive literature review of transit signal priority models was presented. The review was classified into various categories including: *a)* TSP tactics, *b)* transit priority and different signal control systems including fixed-time, coordinated-actuated, fully actuated, and adaptive system, *c)* passive versus active signal priority, and conditional TSP, *d)* transit arrival time and predictive signal priority, *e)* TSP with connected vehicle, *f)* multi-modal signal priority models, and *g)* other practical consideration. There is no one-size-fits-all approach in term of applying TSP. Each transit route has different characteristics and presents various challenges which needs to be addressed differently. Each TSP treatment must be evaluated on a case by case basis. Applying a combination of different transit signal priority models that can work with the state-of-the-art technology would subtly facilitate the movement of transit and provide some performance improvement in transit operations. Most recently, the concept of Complete Streets is being introduced in emerging smart cities. The application of TSP tactics to improve the efficiency of transportation network with all users in mind will integrate well with the Complete Streets approaches. In addition, to make a transit system run faster with higher ridership, specifically busses, a strategy like transit signal priority needs to be applied together with other strategically chosen improvements. These improvements are increasing service, prioritizing transit on city streets (priority in space), redesigning bus networks, balancing bus stops, upgrading technology like fare payment system, etc. Any type of operational improvement should make sense first in order to be implemented in reality.

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