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Multi-modal traffic signal control with priority, signal actuation and coordination

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ABSTRACT

Both coordinated-actuated signal control systems and signal priority control systems have been widely deployed for the last few decades. However, these two control systems are often conflicting with each due to different control objectives. This paper aims to address the conflicting issues between actuated-coordination and multi-modal priority control. Enabled by vehicle-to-infrastructure (v2i) communication in Connected Vehicle Systems, priority eligible vehicles, such as emergency vehicles, transit buses, commercial trucks, and pedestrians are able to send request for priority messages to a traffic signal controller when approaching a signalized intersection. It is likely that multiple vehicles and pedestrians will send requests such that there may be multiple active requests at the same time. A request-based mixed-integer linear program (MILP) is formulated that explicitly accommodate multiple priority requests from different modes of vehicles and pedestrians while simultaneously considering coordination and vehicle actuation. Signal coordination is achieved by integrating virtual coordination requests for priority in the formulation. A penalty is added to the objective function when the signal coordination is not fulfilled. This “soft” signal coordination allows the signal plan to adjust itself to serve multiple priority requests that may be from different modes. The priority-optimal signal timing is responsive to real-time actuations of non-priority demand by allowing phases to extend and gap out using traditional vehicle actuation logic. The proposed control method is compared with state-of-practice transit signal priority (TSP) both under the optimized signal timing plans using microscopic traffic simulation. The simulation experiments show that the proposed control model is able to reduce average bus delay, average pedestrian delay, and average passenger car delay, especially for highly congested condition with a high frequency of transit vehicle priority requests.

1. Introduction

Modern urban transportation networks involve complex traffic dynamics composed of multiple travel modes, including passenger cars, transit buses, pedestrians, bicycles, trucks, light rail, emergency vehicles, and commercial and private modes of transportation. Traffic signal control systems traditionally treat either the aggregated flow of traffic or each mode

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Table 1
Traffic signal control treatments for different traffic modes in current state-of-practice systems in the US.

Traffic mode	Traffic characteristics	State-of-practice treatment
Passenger cars	Mass volume and very low priority	Signal coordination and phase actuation
Buses	Low volume and medium priority	Transit signal priority
Pedestrians	Varying volume and no priority consideration; low speed and high vulnerable	Pedestrian dedicated intervals
Bicycles	Varying volume and no priority; medium speed and high vulnerable	Bicycle dedicated phases
Trucks	Medium to high volume and low priority	Freight signal priority
Light rail	Low volume and high priority	Signal preemption and Transit signal priority
Emergency vehicles	Very low volume and extremely high priority	Signal preemption

separately, as summarized in Table 1. For example, signal coordination aims to generate a "green wave" for passenger cars to progress along a route through several signalized intersections; signal preemption ensures the high priority requests from emergency vehicles are served in a timely fashion; and, transit signal priority (TSP) is widely used to favor bus and light rail movements. Aggregation of the modes into a single flow does not support the desire to provide priority for different modes to meet system operating objectives. Treating each mode separately is likely to result in sub-optimal system performance (He et al., 2012). Different travel modes have their own specific characteristics including travel speed, volume, priority level, and vulnerability, yet very little is understood about the interactions among signal control strategies for the different modes.

Multi-modal signal control systems can be considered as a natural extension of traditional signal priority control systems, which include emergency vehicle preemption and transit signal priority (TSP). An emergency vehicle requests signal preemption treatment by using either optical, acoustic, special inductive loop technology, or based on wireless communications using Global Positioning System (GPS) positions (Nelson and Bullock, 2000). Preemption generally involves a control strategy that immediately switches from the current phase to a pre-selected phase for the first request received. Transit signal priority has been adopted using similar technology, but can be served by minor modifications to traffic signal plan parameters (offset adjustment, green split reallocation, phase insertion or phase rotation) to favor the movements of transit vehicles (Evans and Skiles, 1970; Yagar and Han, 1994; Balke et al., 2000; Furth and Muller, 2000; Skabardonis, 2000; Baker et al., 2002; Head, 2002; Liu et al., 2003; Smith et al., 2005; Skabardonis and Geroliminis, 2008; Ma et al., 2010).

In current emergency vehicle preemption systems, only one request is served at a time. Therefore, if multiple vehicles are simultaneously approaching an intersection and they request conflicting traffic signal phases the first request received would be served even if a safer and more efficient solution could be achieved by considering all active request simultaneously. While emergency vehicle operators are trained to be observant and vigilant, there have been cases where two emergency vehicles have collided in an intersection (ABC13, 2009). Roadway safety has been noted as a significant emergency responder issue (The Transportation Safety Advancement Group, 2010).

TSP is a popular tool for improving transit performance and reliability (Smith et al. 2005). However, state-of-practice TSP is designed for one priority request at a time. Existing priority control systems are not capable of handling conflicting or multiple priority requests. For example, if two buses arrive on conflicting approaches at an intersection during a cycle, it is possible to serve both buses such that the total delay is minimized, but this may not be achieved if a first-come-first-serve policy is used. If the signal is already green for the second vehicle that arrives, the request from the first vehicle, which currently has a red signal, is likely to be served by an early green, which would result in an "early red" for the second vehicle. This would cause more delay than remaining in green to serve the second vehicle, then serving the first vehicle. Not only could this result in increased delay, it can result in increasing the delay variability (e.g. travel time reliability).

Most priority control systems do not address the multi-modal control need (University of Arizona, 2012). Agencies that operate traffic signal systems desire to establish a priority control policy that can favor one mode over another in a specific corridor during a specific time of day. For example, a traffic signal control system may be divided into several control sections based on the traffic flow pattern. One section might be in a region where there are many commercial trucks moving goods from warehouses to the interstate freeway system. Another section might be in a residential area where pedestrians and buses are a popular mode of transportation. The operating agency may want to provide priority for trucks in the first section and priority for pedestrians and transit in the second section. The ability to favor one mode over another is a desirable traffic control system characteristics.

With the advent of Connected Vehicles in United States (Research and Innovative Technology Administration, 2011), it may soon be possible to obtain additional information about the network state and vehicle operations. Connected Vehicles adopt a suite of communication technologies and applications to provide connectivity that includes vehicle-to-vehicle (v2v) communication and vehicle-to-infrastructure (v2i) communication, called v2x in general. Using v2i communication systems, the traffic signal control system can receive requests from equipped vehicles and pedestrians, and can generate an optimal signal timing plan that accommodates all of the active requests and the operating agencies priority policy.

In the past, communication technologies have been applied on transit signal priority (TSP) control projects (Chang et al., 1996; Liao and Davis, 2007; Ekeila et al., 2009). However, very few references can be found that address the multi-priority request issue. Head et al. (2006) proposed a mixed integer program which could accommodate multiple priority requests and minimize the total priority delay. However, deterministic priority vehicle arrival times are assumed in their work, which is reasonable for emergency vehicles but not realistic for transit buses. Recently, several algorithms have developed to resolve multiple transit priority requests (He et al., 2011; Zlatkovic et al., 2012; Ma et al., 2013). However, these studies did not address signal coordination or real-time vehicle actuations. Vehicle actuation can provide advantages when there are gaps in traffic flow. He et al. (2012) proposed a multi-modal signal control formulation called PAMSCOD that considers multi-modal as well as coordination for a group (e.g. section) of traffic signals along an arterial. However, PAMSCOD relies on there being a significant level of v2i communications penetration, e.g. 40% market penetration, and uses a powerful optimization solver, CPLEX, to solve the large and complex optimization problem. PAMSCOD cannot currently be solved for real-time implementation.

To address the market penetration issue, this paper assumes only traffic modes that are priority eligible (such as emergency vehicles, buses and pedestrians) are equipped with v2i communication systems. Passenger cars can only actuate the signals via traditional loop detectors. Pedestrians are traditionally not considered priority eligible, but there is no reason that they could not receive preferential treatment.

Real-time vehicle actuations are very crucial for real-time traffic signal control. To some extent, actuated controllers are themselves "adaptive" in view of their ability to respond to the natural stochastic variations in traffic flow in a manner similar to adaptive control (Zheng and Recker, 2013). Actuated control can be programmed to adapt to vehicle demand by serving phases when there are vehicles present, changing phases lengths as vehicles arrive, forcing-off a phase to achieve coordination goals, and many other operations with the purpose of shifting capacity where and when it is needed. For example, the green time of a phase is extended by detector calls as vehicle approach an intersection. Modeling actuated signal control is complicated since cycle times and phase durations are determined based on actual real-time vehicle demand, which is uncertain by nature. Therefore, it is impossible to derive an exact signal plan for actuated control in advance. However, a flexible signal plan including flexible phase duration times could be generated to accommodate actuation events with priority constraints.

Signal coordination plays an important role in traffic signal control. Coordination aims to provide smooth progression of vehicle platoons through the determination of traffic plans that contain appropriate offsets, splits, and cycle times at each intersection in a section. The benefits that can be obtained from coordination drive the need to develop an analytical framework that simultaneously considers signal coordination and priority. To our best knowledge, there is little literature that examines signal coordination and the priority problem in a single model formulation within a vehicle actuated control strategy.

The control strategy proposed in this paper builds on a mathematical optimization model of traffic signal priority control and a flexible implementation algorithm that considers real-time vehicle actuations and "soft" signal coordination via virtual priority requests. In this paper, three traffic modes are considered: buses, passenger cars and pedestrians, within a decision framework that can accommodate emergency vehicles, railway crossing, trucks, and bicycles. Assumptions are made as follows:

Assumption 1. The sequence of phases in a ring is fixed.

Assumption 2. An existing off-line optimized signal coordination plan is available.

Assumption 1 holds since phase rotation can cause confusion to the motorist, loss of coordination, and long delay to the traffic stream (Skabardonis, 2000). It is understood that phase rotation, such as lead-lag and lag-lead, can produce useful behavior is some circumstances. Assumption 2 assumes an existing offline optimized signal coordination plan that could provide the "soft" coordination priority requests has been developed a priori.

The contributions of this paper are as follows:

- A decision framework is developed that can accommodate multi-modal priority requests, with explicit consideration of the delay impact for passenger cars.
- The concept of signal actuation is leveraged for priority control to fully utilize available phase green time.
- Coordination is achieved at adjacent intersections by using virtual priority requests within the multi-modal decision framework.

This paper is organized as follows: Section 2 presents a mixed integer linear program (MILP) formulation for robust multiple priority control with mixed traffic modes; Section 3 describes how actuated control is implemented within the optimal solution of the robust formulation and how information from real-time vehicle actuations can be used to improve the efficiency of the control strategy by reducing the delay for passenger vehicles; Section 4 presents a numerical example comparing to the state-of-practice strategies; and, concluding remarks along with future extensions are reported in the Section 5.

A summary of the model notation is presented in Table 2.

2. MILP formulation

The standard NEMA dual-ring, eight-phase structure is considered in this paper. A four-legged intersection with eight movements is shown in Fig. 1(a). Typically, each ring in the controller contains 4 phases, depicted in Fig. 1(b). A barrier exists that crosses both rings between groups of conflicting movements so that all phases in one group have to terminate before any phase in the next group starts.

Table 2
Symbol definition of sets, decision variables and data.

Type	Symbol	Definition
Sets	$i \in I$	The set of rings
	$p, p', q, l \in P$	The set of phases
	$p \in P_c$	The set of coordination phases
	$m \in M$	The set of priority modes (such as emergency vehicles, transit buses, and pedestrians)
	$k, k' \in \{1, 2, \ldots, K\}$	The set of cycles
	$j \in J$	The set of number of requests
	$(p, q) \in B$	The set of barriers. Phase p and q belong to two different rings. Ending time of phase p needs to be equal to the starting time of phase q. In this paper, we define $B = \{(2, 7), (6, 3)\}$, consistent with the ring structure depicted in Figure. 1
	$(p', k') = \mathrm{H}^{+}(p, k)$	The next timing phase after timing phase p during cycle k
	$(m, j, p) \in \Gamma$	The set of all active priority requests
Decision variables	D^{P}_{mjp}	Delay for priority request (m,j,p)
	D^{V}_{pk}	Total vehicle delay at current intersection for phase p during cycle k
	D^{C}_{pk}	Passenger vehicle delay at downstream intersections due to lack of coordination for phase $p \in P_c$ during cycle k
	e_{pk}	Maximal available green extension time for actuated control at phase p during cycle k
	g_{pk}	Green time for phase p during cycle k
	g'_{pk}	Necessary green time for phase p during cycle k starting from t'_{pk}
	Q^{R}_{pk}	Residual queue length at ending time of phase p at cycle k
	t_{pk}	Starting time of phase p during cycle k
	t'_{pk}	Latest starting time of phase p during cycle k
	τ_k	Starting time of cycle k, (each cycle starts from a pair of initial phases)
	v_{pk}	Phase duration time of phase p during cycle k, including clearance time
	v'_{pk}	Maximal phase duration time of phase p during cycle k, including clearance time
	Z_{pk}	Number of vehicle exiting from intersection at phase p during cycle k
	θ_{mjpk}	0–1 Binary variables for assigning a priority request to a cycle (if $\theta_{mjpk} = 1$, the priority request (m,j,p) is served in cycle k; else, not served in cycle k)
	ω_{mjpk}	0–1 Binary dummy variables($\omega_{mjpk} = 1$ when $\theta_{mjpk'} = 1$ and $k' \leqslant k$, otherwise $\omega_{mjpk} = 0$)
Data	a_{lp}	0–1 Binary data ($a_{lp} = 1$ when phase p and l are in the same ring and phase l times before phase p, otherwise $a_{lp} = 0$)
	b_{ip}	0–1 Binary data ($b_{ip} = 1$ when phase p belongs to ring i, otherwise $b_{ip} = 0$)
	C	Common cycle length for signal coordination
	λ_p	Vehicle arrival rate (veh/s) at phase p
	σ	Coefficient to estimate passenger vehicle delay at downstream intersection due to early green
	$g^{\min}_{pk}$	Minimal green time for phase p during cycle k
	$g^{\max}_{pk}$	Maximal green time for phase p during cycle k
	g^{Ped}_{pk}	Required pedestrian interval (including both walk time and clearance time) for phase p during cycle k
	G^{M}_{mjp}	Needed green time to clear the moving platoon before priority vehicle with request (m,j,p)
	G^{Q}_{mjp}	Needed green time to clear the standing queue before priority vehicle with request (m,j,p)
	K	Total number of cycle in optimization horizon
	M	A very large positive number
	$n_{pt}(\tau)$	Number of vehicle actuations on phase p from time $t - \tau$ to time t
	O	Offset for the current intersection
	Q^{0}_{p}	Initial queue at phase p
	r_p	Red clearance time for phase p
	R_{mjp}	Time of arrival for priority request (m,j,p)
	R'_{pk}	Time of virtual coordination request at coordination phase $p \in P_c$ and cycle k
	s_p	Saturation flow rate (veh/s) at phase p
	t_0	Initial time of optimization horizon
	w^{P}_{mjp}	Weight for delay from priority request (m,j,p)
	w^{V}	Weight for delay from passenger vehicles
	w^{C}	Weight for delay from coordination requests
	y_p	Yellow clearance time for phase p
	ε	A small positive fractional number

The dual-ring controller can be modeled by a traditional precedence graph as depicted in Fig. 2 (Head et al. 2006). Arcs in the precedence graph represents the duration of phases, while nodes represents the phase transitions. Phase intervals can be easily visualized in the precedence graph by decomposing each arc into its respective interval precedence graph.

The precedence graph defines the phase relationships and green time feasible region. Traditionally, a signal plan is modeled by pre-allocated phase splits v_{pk}, where $v_{pk} = g_{pk} + y_p + r_p$, as shown in Fig. 3(a) and includes the green, yellow change, and red clearance intervals. However, it is difficult for this signal model to represent the existing practical control logic of actuated control. In this paper, we propose a flexible signal model to include the concept of green extension in actuated signal control, as shown in Fig. 3(b). A flexible phase duration time v'_{pk} is defined as $v'_{pk} = g'_{pk} + e_{pk} + y_p + r_p$, which

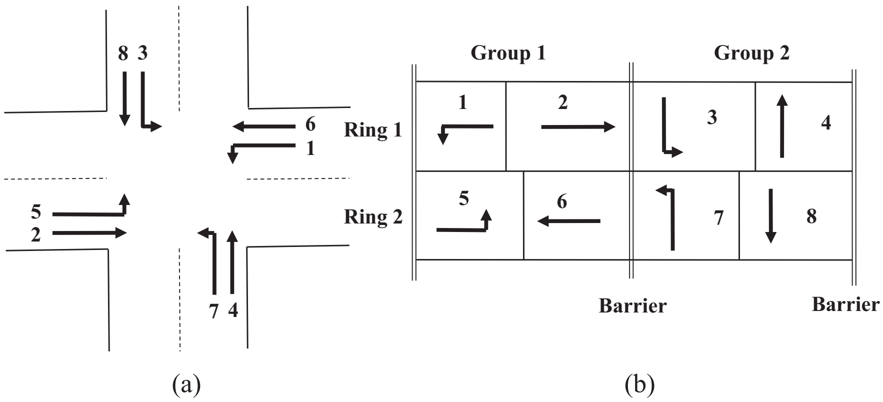

Fig. 1. (a) Intersection layout showing associated phases. (b) Dual ring, eight phase controller model.

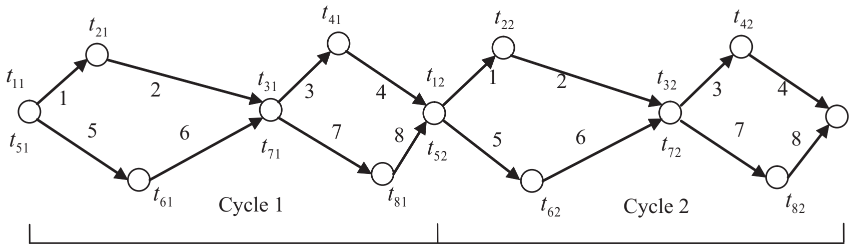

Fig. 2. Precedence graph representation of a dual-ring controller.

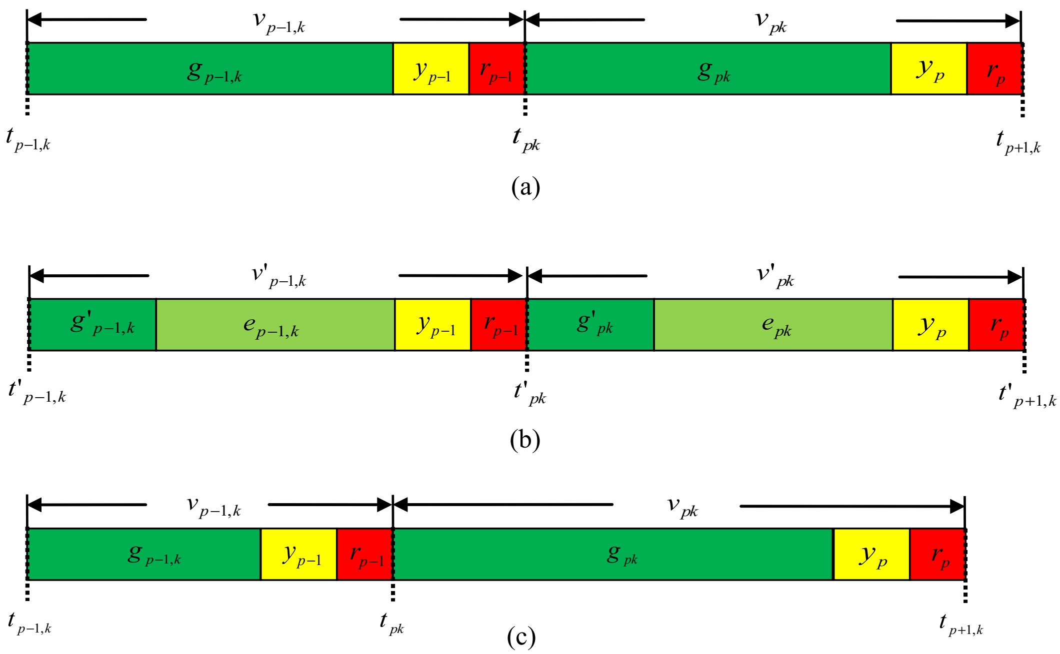

Fig. 3. (a) Representation of a traditional signal plan for fixed time control; (b) representation of a flexible signal plan for actuated control; and (c) a realization of flexible signal plan in (b).

consists of three components: necessary green time g'_{pk}, additional maximal possible green extension time e_{pk} and change and clearance time $y_p + r_p$. Necessary green time can be interpreted as the minimal green time required to accommodate future priority requests. Thus, it is equivalent to the maximum of between phase minimal green time and the green time required to serve active priority requests. The necessary green duration is guaranteed, while green extension is optional. For example, the duration of phase p could be extended as long as $g'_{pk} + e_{pk}$. There are two stages to implement the flexible phase. In the first stage, the controller holds phase p green for g_{pk} seconds. After it times out, the controller implements actuated control logic with real-time demand actuating the phase for each detected vehicle by adding the programmed extension time up to e_{pk} seconds when the phase is forced-off. Given this new flexible behavior, traditional v_{pk} and t_{pk} are replaced by v'_{pk} and t'_{pk}, which denote maximal phase duration time and the latest starting time of phase p at cycle k, respectively. In other words, phase p in cycle k could start timing before t'_{pk}. One possible realization of a flexible plan is illustrated in Fig. 3(c). An algorithm for assigning the green extension is proposed in Section 3 for real-time vehicle actuations.

A MILP model is presented as follows:

$$\text{Minimize} \sum_{(m,j,p)\in\Gamma} w^P_{mjp} D^P_{mjp} + \sum_k \sum_p w^V D^V_{pk} + \sum_k \sum_{p\in P_c} w^C D^C_{pk} - \varepsilon \sum_k \sum_p e_{pk} (MILP) \tag{1a}$$

Subject to

Constraints of phase precedence:

$$t'_{pk} = \tau_k + \sum_{l\in P} a_{lp} v'_{lk} \quad \forall p,k \tag{1b}$$

$$\tau_{k+1} = \tau_k + \sum_p b_{ip} v'_{pk} \quad \forall i,k \tag{1c}$$

$$t'_{pk} + v'_{pk} \leqslant t'_{qk} \quad \forall k,(p,q) \in B \tag{1d}$$

$$\tau_1 = t_0 \tag{1e}$$

$$v'_{pk} = g'_{pk} + e_{pk} + y_p + r_p \quad \forall p,k \tag{1f}$$

$$g'_{pk} \geqslant g^{\min}_{pk} \quad \forall p,k \tag{1g}$$

$$g'_{pk} + e_{pk} \leqslant g^{\max}_{pk} \quad \forall p,k \tag{1h}$$

Constraints of queue dynamics:

$$Q^R_{p,k+1} \geqslant Q^R_{pk} + (t'_{p,k+1} + g'_{p,k+1} + e_{p,k+1} - (t'_{pk} + g'_{pk} + e_{pk}))\lambda_{pk} - (g'_{p,k+1} + e_{p,k+1})s_p \quad \forall p,k \tag{1i}$$

$$Q^R_{p1} \geqslant Q^0_p + \lambda_{p1}(t'_{p1} + g'_{p1} + e_{p1} - \tau_1) - (g'_{p1} + e_{p1})s_p \quad \forall p \tag{1j}$$

Constraints of serving priority requests:

$$R_{mjp} \leqslant t'_{pk} + g'_{pk} + (1 - \theta_{mjpk})M \quad \forall (m,j,p) \in \Gamma, m \neq '\text{Pedestrian}', k \tag{1k}$$

$$R_{mjp} \leqslant t'_{pk} + g^{Ped}_{pk} + (1 - \theta_{mjpk})M \quad \forall (m,j,p) \in \Gamma, m =' \text{Pedestrian}', k \tag{1l}$$

$$\sum_k \theta_{mjpk} = 1 \quad \forall (m,j,p) \in \Gamma \tag{1m}$$

$$\sum_{k'=1}^{k} g'_{pk'} \geqslant G^Q_{mjp} + G^M_{mjp} - (1 - \omega_{mjpk})M \quad \forall (m,j,p) \in \Gamma, k \tag{1n}$$

$$\omega_{mjpk} = \sum_{k'=1}^{k} \theta_{mjpk'} \quad \forall (m,j,p) \in \Gamma, k \tag{1o}$$

Constraints of delay evaluation:

$$D^P_{mjp} \geqslant t'_{pk} + G^Q_{mjp} + G^M_{mjp} - R_{mjp} - (1 - \theta_{mjpk})M \quad \forall (m,j,p) \in \Gamma, k \tag{1p}$$

$$D^V_{pk} \geqslant \frac{\lambda_{pk}(C^{nom} - g^{nom}_p)(t'_{p,k+1} - t'_{pk} - g'_{pk} - e_{pk})}{2(1 - \frac{\lambda_{pk}}{s_p})} + C^{nom} Q^R_{pk} \quad \forall p,k \tag{1q}$$

$$D^C_{pk} \geqslant t'_{pk} - R'_{pk} \quad \forall p \in P_c, k \tag{1r}$$

$$D^C_{pk} \geqslant \sigma(R'_{pk} - t'_{pk}) \quad \forall p \in P_c, k \tag{1s}$$

$$\theta_{mjpk}, \omega_{mjpk} \in \{0, 1\} \quad \forall (m,j,p) \in \Gamma, k$$

$$D^P_{mjp}, D^V_{pk}, D^C_{pk}, e_{pk}, g'_{pk}, v'_{pk}, t'_{pk}, Q^R_{pk} \geqslant 0 \quad \forall (m,j,p) \in \Gamma, k$$

The objective of the mathematical model is to minimize the total weighted delay for active priority requests, passenger vehicles and virtual coordination requests. The weights w_{mjp} can be considered as a function of real-time bus occupancy and adherence of schedule or as mission priority for emergency vehicles. Coefficient w^C adjusts the weight of penalty of dissatisfying virtual coordination requests, which will be further explained in the following discussion.

When the traffic demand is low, the benefit gained from coordination is not significant. Therefore, w^C could be a relative small number (e.g. 0.1–0.5). When traffic becomes heavy during the peak hour, coordination plays an important role to reduce the total delay along the arterial. Thus w^C should be set higher to help maintain coordination (e.g. 0.5–1), but should likely be lower than priority requests. The last item in (1a), $\varepsilon\sum_k\sum_p e_{pk}$, aims to maximize the total extension times, which increase the flexibility of optimal signal plans to respond to real-time vehicle actuations. Since flexibility is probably not very important, ε is a generally a very small positive fractional number.

Constraints (1b)–(1h) represent a flexible dual-ring controller structure starting at t_0 and considering K total cycles, depicted in Fig. 2. Barrier constraint (1d) ensures the starting time of phase 3 and 7 are the same. In this paper, we define $B = \{(2, 7), (6, 3)\}$, consistent with ring structure depicted in Figs. 1 and 2. When both $t'_{2k} + v'_{2k} \leqslant t'_{7k}$ and $t'_{6k} + vt'_{6k} \leqslant t'_{3k}$ are satisfied, we will have $t'_{3k} = t'_{7k}$ due to connectivity in each ring. The model of actuated control is addressed with constraint (1f)–(1h).

Constraints (1i) and (1j) model queue dynamics in the signal plan by calculating residual queue length Q^R_{pk}. Here it is assumed that the arrival rate is constant and deterministic.

Constraints (1k)–(1o) describe two conditions to serve a priority request: (1) The arrival time of priority request should be before the ending time of the necessary green during cycle k, when the request will be served. Constraint (1k) and (1l) are cycle selection constraints, which select cycle k to serve requests (m,j,p,k). Binary variables θ_{mjpk} are introduced to address the combinatorial optimization problem. If $\theta_{mjpk} = 1$, request (m,j,p) can be served only by phase p during cycle k, and (1k) become a valid inequality; otherwise, it is relaxed. Therefore, $\sum_m\sum_j\theta_{mjpk}$ is equal to the number of request to be served during phase p of cycle k. (1l) is specially defined for pedestrian control intervals which consists of both walk time and pedestrian clearance time. In this paper, we assume g^{Ped}_{pk} is a given parameter and equal to the summation of walk time and pedestrian clearance time. We optimize the start time of pedestrian intervals but do not consider the duration of pedestrian intervals as decision variables. It is possible to include the walk interval as a decision variable, but pedestrian clearance is a constant. Frequently, g^{Ped}_{pk} is longer that the necessary vehicle phase service time due to the distance that pedestrians are required to walk. In this case, (1l) becomes the critical path in the precedence relationship for the associate phase. However, it is possible that the pedestrian intervals could require less time than the associate phase due to a narrow crossing or due to high vehicle demand. In this case, the current model could be enhanced with minor changes to allow the walk interval to be a decision variable and extend to some maximum time. This is called "walk rest" in modern traffic signal controllers. Cumulative cyclic green time should be greater than the needed green time to clear both stop-bar queue and moving platoon before a priority request, illustrated in inequality (1n) and in Fig. 4. Constraint (1o) introduces dummy binary variables ω_{mjpk}, which are equal to 1 if the request is served between cycle 1 and k, otherwise 0. When $\theta_{mjpk} = 1$, inequality (1o) is valid in cycle k, $k + 1, \ldots, K$.

Constrain (1p) assesses priority request weighted delay. According to Fig. 4, the priority vehicle has to be served after the standing queue at the stop-bar (which needs G^Q_{pk} green time to clear) and the vehicles preceding the priority vehicle in the platoon (which needs G^M_{pk} green time to clear). So the priority delay is $D^P_{mjp} = t'_{pk} + G^Q_{pk} + G^M_{pk} - R_{mjp}$ when request (m,j,p) is served in cycle k. G^Q_{pk} can be calculated by real-time queue length estimation, which is not in the scope of this research. One may refer to recent literature for detailed algorithms (Skabardonis and Geroliminis, 2008; Liu et al., 2009; Viti and van Zuylen, 2010; Wu and Liu, 2014). G^Q_{pk} can be estimated by upstream stop-bar detector and the time the priority vehicle passes the upstream intersection (Skabardonis and Geroliminis, 2008).

Constraint (1q) models approximate passenger vehicle delay using a deterministic queuing model. To avoid loss of generality, the residual queue is incorporated into the model when flow is very close to saturation. Given saturated conditions, it may take most of the green time to serve the new arrivals. Therefore, the residual queue may need to wait nearly the whole cycle to be served. Newell (1965) recommended a hypothetical queue discipline of "last come first served" in which the residual queues are kept in the queue until any new arrivals have been served. Thus the total delay in phase p during cycle k can be approximated by a expression as follows,

$$Delay \sim \frac{\lambda_{pk}(t'_{p,k+1} - t'_{pk} - g'_{pk} - e_{pk})^2}{2\left(1 - \frac{\lambda_{pk}}{s_p}\right)} + (t'_{p,k+1} - t'_{pk})Q^R_{p,k-1} \tag{1t}$$

where $(t'_{p,k+1} - t'_{pk} - g'_{pk} - e_{pk})$ represents effective red time and $(t'_{p,k+1} - t'_{pk})$ is the cycle time at cycle k. To make expression (1t) linear, passenger vehicle delay is approximated in inequality (1q) by replacing one of $(t'_{p,k+1} - t'_{pk} - g'_{pk} - e_{pk})$ and $(t'_{p,k+1} - t'_{pk})$ with nominal red effective time $(C^{nom} - g^{nom}_p)$ and nominal cycle time C^{nom}, respectively. From a variety of

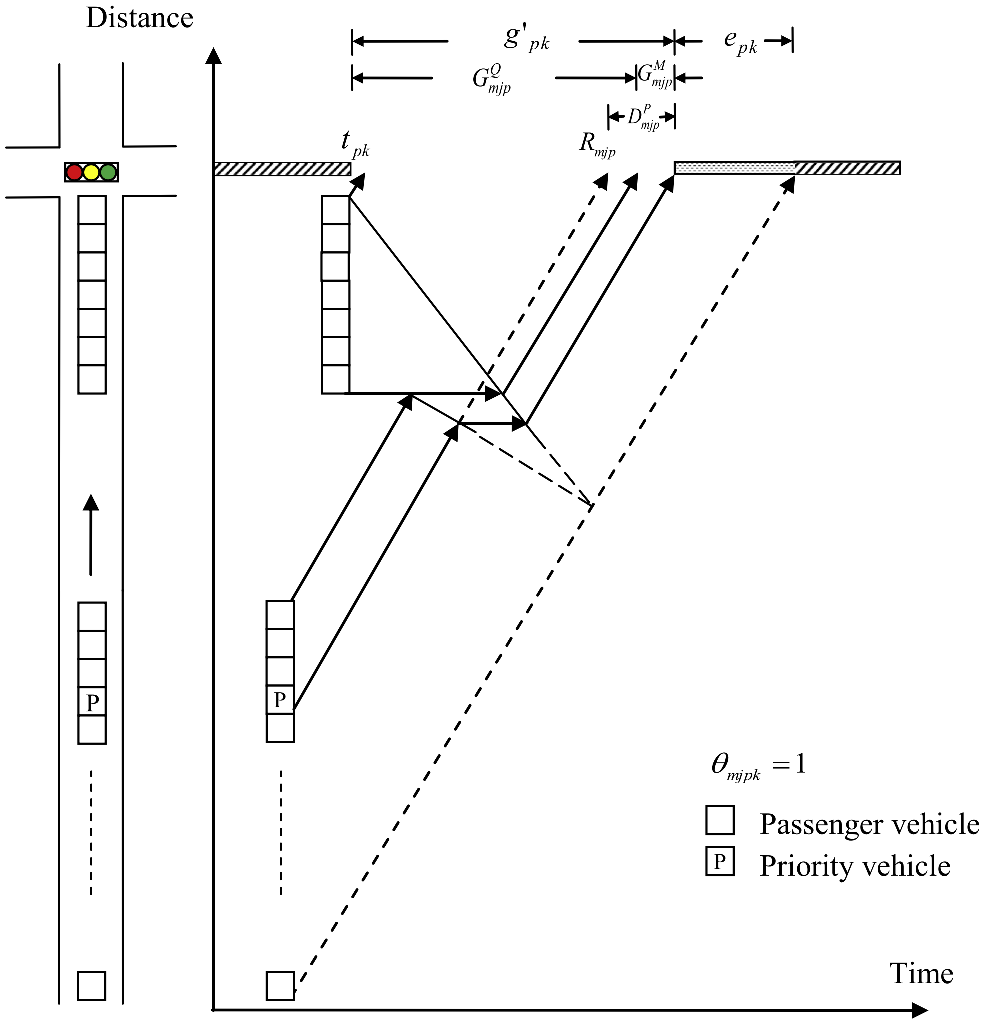

Fig. 4. Priority vehicle service cycle selection and delay evaluation.

simulation experiments it was observed that the mean average percentage error (MAPE) of queue size is approximately 10%, which seems sufficient for the purpose of traffic signal control, especially when actuations are allowed to extend or terminate phases based on the presence of vehicles.

Constrains (1r) and (1s) address coordination issues by introducing virtual coordination requests at each intersection. Virtual coordination requests are priority requests intent on creating a "green wave" for passenger vehicles. Given pre-calculated or an online optimized signal coordination plan, the "arrival times" R^{prime}_{pk} of virtual coordination requests are generated to request coordination phase p for each cycle k, shown as Fig. 5. The total number of virtual coordination requests is equal to N_cK, where N_c is the number of coordination phases (phase 2 and phase 6 for this study), and K is the number of cycles considered. Such virtual requests are included every time the formulation is solved. The penalty for lack of coordination is measured by D^C_{pk} in inequalities (1r) and (1s). Note that (1r) assesses late green starting time, while (1s) evaluates early green starting time, which is still not desirable because of potential stops at downstream intersections. In this paper, we set delay weight σ to 0.6 based on empirical experience.

Signal coordination parameters, such as offsets and common cycle length, can be easily modified according to the traffic demand. MILP automatically generates the optimized plan for given different coordination parameters. The coordination parameters can be provided by some signal optimization software, such as TRANSYT (Wallace et al., 1998), SYNCHRO (Trafficware, 2009) or PASSER (Chaudhary and Chu, 2003). By adding coordination requests to the formulation, solving one program for each intersection separately will result in signal coordination. Therefore, overall arterial signal coordination problems are actually decomposed into sub-problems at each intersection. The computation load is reduced dramatically in this way.

When traffic is saturated, a preferable alternative objective is to maximize the throughput of passenger vehicles and minimize the delay of priority vehicles:

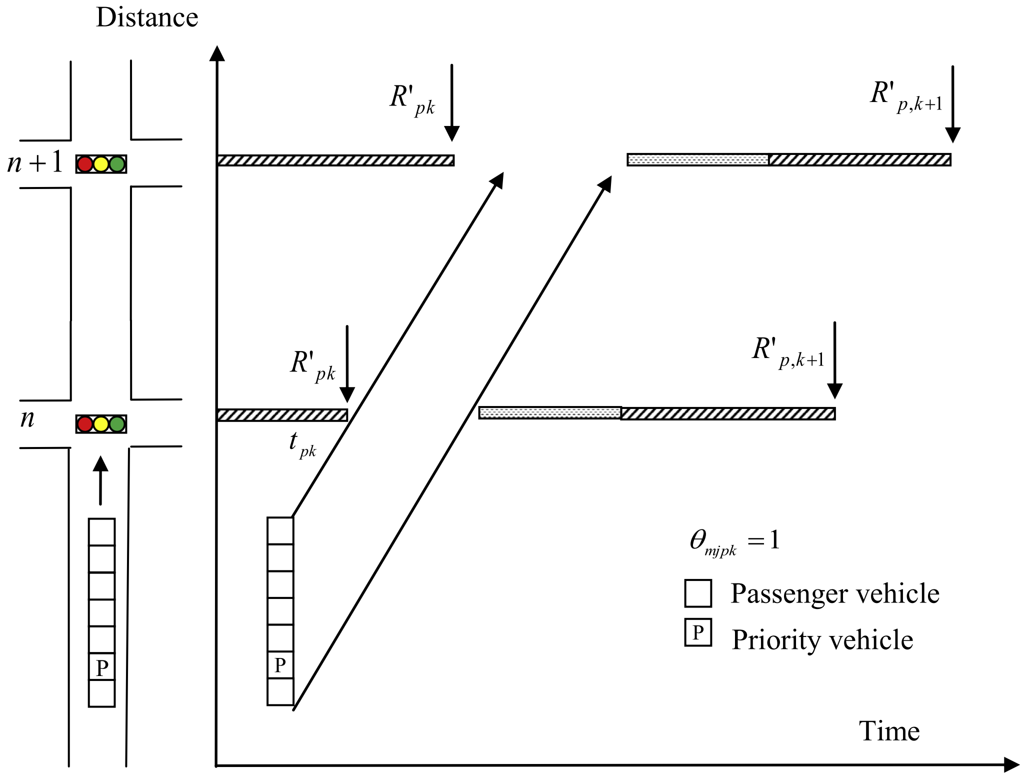

Fig. 5. Modeling signal coordination by virtual requests.

$$\text{Minimize} \sum_{(m,j,p)\in\Gamma} w_{mjp} D^P_{mjp} - \beta \sum_k \sum_p Z_{pk} + \alpha \sum_k \sum_{p\in P_c} D^c_{pk} - \varphi \sum_k \sum_p e_{pk}$$

$$Z_{pk} = Q^R_{p,k-1} + \lambda_{pk}(t'_{pk} + g'_{pk} + e_{pk} - (t'_{p,k-1} + g'_{p,k-1} + e_{p,k-1})) - Q^R_{pk} \quad \forall p, k > 1$$

$$Z_{p1} = Q^0_p + \lambda_{p1}(t'_{pk} + g'_{pk} + e_{pk} - \tau_1) - Q^R_{p1} \quad \forall p$$

$$Z_{pk} \geqslant 0 \quad \forall p, k$$

where Z_{pk} represents the total number of vehicles departing in phase p at cycle k.

Although the above MILP includes green extension and signal coordination, it does not specifically consider the randomness of passenger vehicle arrivals (at rate λ_{pk}) and uncertainty in priority vehicle arrival times R_{mjp}. Thus the optimal solutions could be degraded if the actual arrivals are realized in such a way that they deviates from the assumed rates and times significantly. To make the formulation more robust, we assume that the passenger vehicle arrival rate λ_{pk} and priority vehicle arrival times R_{mjp} are random, and they belong to a pre-defined uncertainty sets (Yin, 2008; Li, 2011). In particular, a box uncertainty set is used,

$$\lambda_{pk} \in U_G \equiv [\underline{\lambda}_{pk}, \overline{\lambda}_{pk}] = [\lambda^*_{pk}(1-\mu^\lambda), \lambda^*_{pk}(1+\mu^\lambda)]$$

$$R_{mjp} \in U_R \equiv [\underline{R}_{mjp}, \overline{R}_{mjp}] = [R^*_{mjp}(1-\mu^R_m), R^*_{mjp}(1+\mu^R_m)]$$

where both λ^*_{pk} and R^*_{mjp} are positive nominal values of λ_{pk} and R_{mjp}, respectively, with positive coefficients μ^λ and μ^R_m, which can be used to adjust "the price of robustness". Note that μ^R_m is associated with priority requests from different modes. The different priority modes generally show different variance of uncertainty. For example, arrival times of emergency vehicle and light rail transit (LRT) are much more accurate than the arrival times of buses. Therefore, constraints (1i)–(1q) can be rewritten as the following robust constraints:

Constraints of queue dynamics:

$$Q^R_{p,k+1} \geqslant Q^R_{pk} + (t'_{p,k+1} + g'_{p,k+1} + e_{p,k+1} - (t'_{pk} + g'_{pk} + e_{pk}))\lambda^*_{pk}(1+\mu^\lambda) - (g'_{p,k+1} + e_{p,k+1})s_p \quad \forall p, k \tag{2i}$$

$$Q^R_{p1} \geqslant Q^0_p + \lambda^*_{p1}(1+\mu^\lambda)(t'_{p1} + g'_{p1} + e_{p1} - \tau_1) - (g'_{p1} + e_{p1})s_p \quad \forall p \tag{2j}$$

Constraints of serving priority requests:

$$R^*_{mjp}(1+\mu^R_m) \leqslant t'_{pk} + g'_{pk} + (1-\theta_{mjpk})M \quad \forall (m,j,p) \in \Gamma, m \neq \text{'Pedestrian'}, k \tag{2k}$$

$$R^*_{mjp}(1+\mu^R_m) \leqslant t'_{pk} + g^{Walk}_{pk} + (1-\theta_{mjpk})M \quad \forall (m,j,p) \in \Gamma, m =\text{' Pedestrian'}, k \tag{2l}$$

$$\sum_k \theta_{mjpk} = 1 \quad \forall (m,j,p) \in \Gamma \tag{2m}$$

$$\sum_{k'=1}^{k} g'_{pk'} \geqslant G^Q_{mjp} + G^M_{mjp} - (1-\omega_{mjpk})M \quad \forall (m,j,p) \in \Gamma, k \tag{2n}$$

$$\omega_{mjpk} = \sum_{k'=1}^{k} \theta_{mjpk'} \quad \forall (m,j,p) \in \Gamma, k \tag{2o}$$

Constraints of various delay evaluation:

$$D^P_{mjp} \geqslant t'_{pk} + G^Q_{mjp} + G^M_{mjp} - R^*_{mjp}(1-\mu^R_m) - (1-\theta_{mjpk})M \quad \forall (m,j,p) \in \Gamma, k \tag{2p}$$

$$D^V_{pk} \geqslant \frac{\lambda^*_{pk}(1+\mu^\lambda)(C^{nom} - g^{nom}_p)(t'_{p,k+1} - t'_{pk} - g'_{pk} - e_{pk})}{2\left(1 - \frac{\lambda^*_{pk}(1+\mu^\lambda)}{s_p}\right)} + C^{nom}Q^R_{pk} \quad \forall p, k \tag{2q}$$

Note that the above formulation is solved only for one intersection whenever there is any change in the list of active priority requests or the optimization interval is reached. When implemented in real-time, the formulation should be adjusted to match its starting phases to the current timing phases (He et al., 2012). Signal coordination is automatically achieved by adding multiple coordination requests. Therefore, the number of integer variables in the formulation is equal to $2K|\Gamma|$, where $|\Gamma|$ indicates the number of active priority requests, and K is the number of cycles considered. Since there is likely to be only a few co-existing priority requests and only two to three cycles considered, the number of total "hard" variables is relatively small. The formulation was tested with CPLEX 12.3 on a PC with a dual core 2.67-GHz processor and 3.5 Gb of memory. In the worst cases, the solution times are less than 1 s. So the proposed MILP formulation is feasible for real-time applications.

3. Signal plan implementation with actuated control

The "optimal" solutions obtained from MILP formulation are not really optimal, since the real-time traffic demand for each phase still is unknown due to the stochastic nature of traffic flow at the individual vehicle level. Existing state-of-practice coordinated-actuated (semi-actuated) control systems handle this issue as well as signal coordination by implementing both concepts of vehicle actuations and force-offs. Vehicle actuations allow controllers to adaptively adjust green time according to different real-time demand, while force-off points maintain signal coordination by terminating the green extension at certain points. Force-off modes can be usually categorized as fixed force-off and floating force-off. Fixed force-offs keep the fixed phase termination time points, while floating force-off only monitor the limit of green time for each phase (Federal Highway Administration, 2009).

In order to implement the optimized signal plan into real-world actuated signal controller, we develop a actuated signal control procedure, which includes two different force-off control modes, ***modified*** fixed and floating force-offs. On one hand, modified fixed force-offs are designed for "priority phases", which serve either virtual coordination requests or priority requests during the phase. As discussed before in Section 2, $\sum_m \sum_j \theta_{mjpk}$ is equal to the number of request to be served during phase p at cycle k. So "priority phase" can be identified from the condition: $\sum_m \sum_j \theta_{mjpk} > 0$. Modified floating force-offs are implemented for "non-priority" phases, where no active request is served: $\sum_m \sum_j \theta_{mjpk} = 0$.

The actuated control procedure is illustrated in Fig. 6. The control logic starts from current time t for initial phase p at cycle k. We check to determine if phase p is a "priority phase" or a "non-priority phase" by calculating $\sum_m \sum_j \theta_{mjpk}$. For priority phases ($\sum_m \sum_j \theta_{mjpk} > 0$), the modified fixed force-off procedure is applied. Modified fixed force-offs maintain the hard starting point (t'_{pk}), soft ending point ($t'_{pk} + g'_{pk}$) and hard ending point ($t'_{pk} + g'_{pk} + e_{pk}$) within the cycle. It guarantees that the phase times between the hard starting point and soft ending point. *If a previous phase ends early, the following phase is allocated the extra time up to at least the soft ending point of the previous phase*; The phase is allowed to gap out if vehicle actuations are not observed ($n_{pt}(\tau) = 0$) and the soft ending point is reached ($t + g_{pk} \geqslant t_{pk} + g'_{pk}$), otherwise it can continue to time up to the hard ending point (check if $t + g_{pk} \geqslant t'_{pk} + g'_{pk} + e_{pk}$, which is equivalent to "max-out").

For "non-priority" phases ($\sum_m \sum_j \theta_{mjpk} = 0$), we implement modified floating force-offs. Modified floating force-offs only check the accumulated green time g_{pk}, and do not check the value of current time t. Such control logic limits the minimal

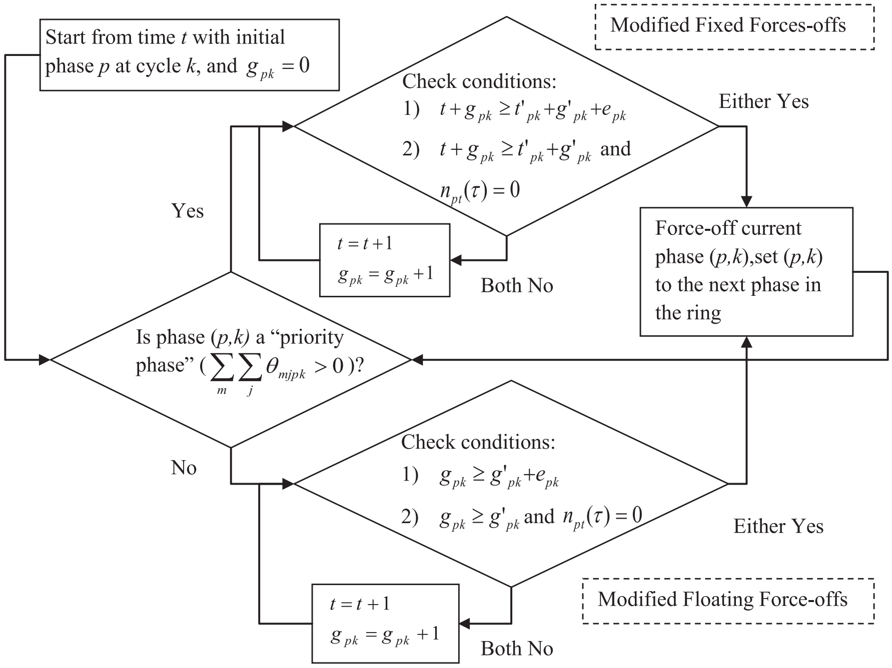

Fig. 6. Actuated control procedure for signal plan implementation.

duration (g'_{pk}) and maximal duration ($g'_{pk} + e_{pk}$) of the phase green time. If no vehicle actuations are observed ($n_{pt}(\tau) = 0$) after the minimal duration is satisfied ($g_{pk} \geq g'_{pk}$), the phase will gap out. Unused green times will be allocated to the following phases. In this paper, we only present the control logic for one ring. The proposed algorithm can be easily modified for a dual-ring structure with additional barrier constraints.

An illustrative example is shown in Fig. 7(a). Phases sequenced along the 1st ring within 2 cycles are represented as a sequence of phases denoted $\phi1$, $\phi2$, $\phi3$, $\phi4$, $\phi1$, $\phi2$, $\phi3$, $\phi4$. Four priority request intervals are given, two of them are transit bus priority requests (travel mode is defined as 'b') on phase 2 and phase 4, denoted as R_{b14} and R_{b22}, and two of them are virtual coordination requests, R_{c12} and R_{c22}. The optimal signal plan and cycle service selection variables, $\sum_m \sum_j \theta_{mjpk}$, are obtained from the MILP solution. For the sequence of phase $\phi1$, $\phi2$, $\phi3$, $\phi4$, $\phi1$, $\phi2$, $\phi3$, $\phi4$, the corresponding value of $\sum_m \sum_j \theta_{mjpk}$ for each of the phases can be represented as the sequence 01010200, where the first bus priority request is served in phase 4 of cycle 1, the second in phase 2 of cycle 2, and the two virtual coordination requests are served in phase 2 of cycle 1 and cycle 2, respectively. All these "priority phases", including phase 2 and 4 in cycle 1 and phase 2 in cycle 2, should be controlled using modified fixed force-offs, while the other phases controlled using the modified floating force-offs.

Implementation of phase 2, 3 and 4 in the second cycle is depicted in Fig. 7(b) using a cycle style diagram. First, $\phi2$ is under modified fixed force-off control, with the start time before the hard starting point at $t = 100$ s and held until the soft ending point $t = 125$ s. Then $\phi2$ can be extended by real-time vehicle actuations until it either gaps out or it reaches the hard ending point at $t = 135$ s. After $\phi2$ terminates, $\phi3$ starts the modified floating control mode, timing for at least necessary green time, g'_{32}, and gaps out by either vehicle-actuations or its maximum green time, or until the remaining green extension time is used. The same procedure is used to time $\phi4$ after $\phi3$ terminates. Therefore, the 'optimal' solutions from MILP formulation are implemented for both coordination and transit bus priority requests.

One of the principle goals of this paper is to show how the MILP formulation can address multiple priority requests within coordinated traffic control as well as allowing actuated phase control to accommodate uncertain vehicle flow as measured through vehicle detection.

Integration of the MILP formulation and actuated control will result in the phases being allowed to gap out if no vehicles are detected, extending the phase if a priority request can be served, or forcing-off the phase when the maximal green extension is reached. Therefore, the efficiency of green time usage is improved for passenger cars.

4. Numerical experiments

The proposed robust multiple priority policy was implemented with VISSIM, a microscopic simulation tool. To better simulate the real traffic signal controller logic, the ASC/3 SIL (software in the loop) controller was installed with VISSIM. The ASC/3 SIL feature allows a VISSIM user to utilize the same logic as a physical ASC/3 controller during the simulation. This includes the transit signal priority (TSP) provided as an advanced feature of the controller firmware (Econolite, 2009).

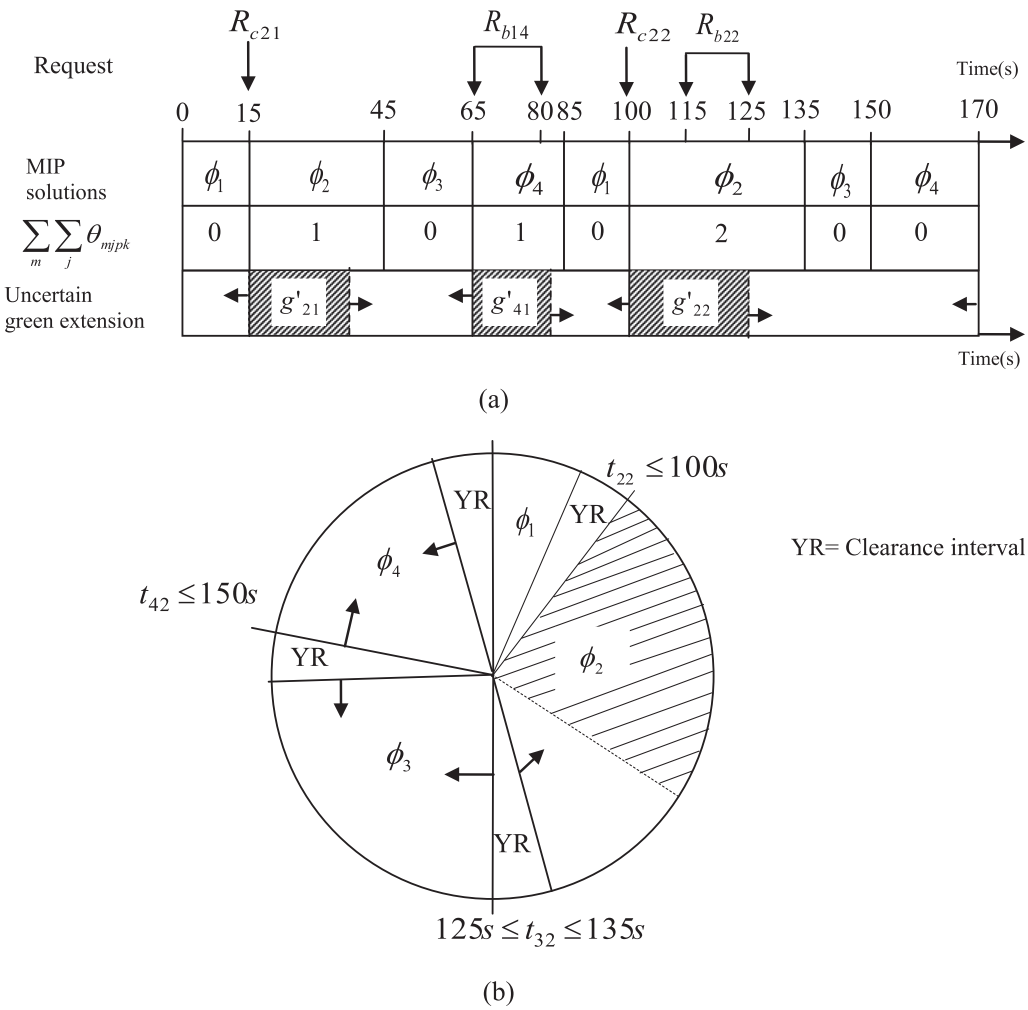

Fig. 7. (a) An example of MILP signal plan solutions; and (b) actuated control for 2 cycles.

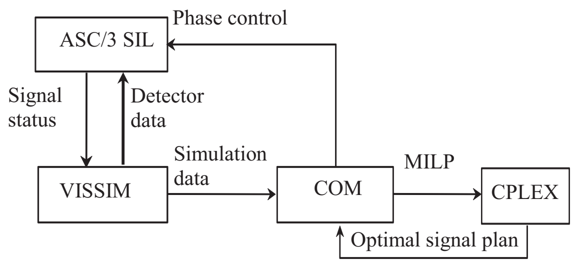

Fig. 8. The evaluation platform.

The entire evaluation platform contains VISSIM with COM (Component Object Model) and the ASC virtual controller as the simulation environment and GAMS/CPLEX as optimization solver, as depicted in Fig. 8. Simulation objects in VISSIM can be accessed and controlled using COM, introduced by Microsoft to enable inter-process communication. First, COM starts a VISSIM simulation and continuously obtains simulation data, including real-time signal timing, detector data, and priority requests. We assume the initial queue length at each cycle can be estimated within tolerance errors. When there is no priority request the actuated control logic is performed by the ASC/3 SIL automatically. When a priority request is received, a MILP program is formulated by the COM component and sent to GAMS/CPLEX. After retrieving optimal signal plan from optimal solutions, the COM component implements the signal timing schedule by sending phase control commands (hold,

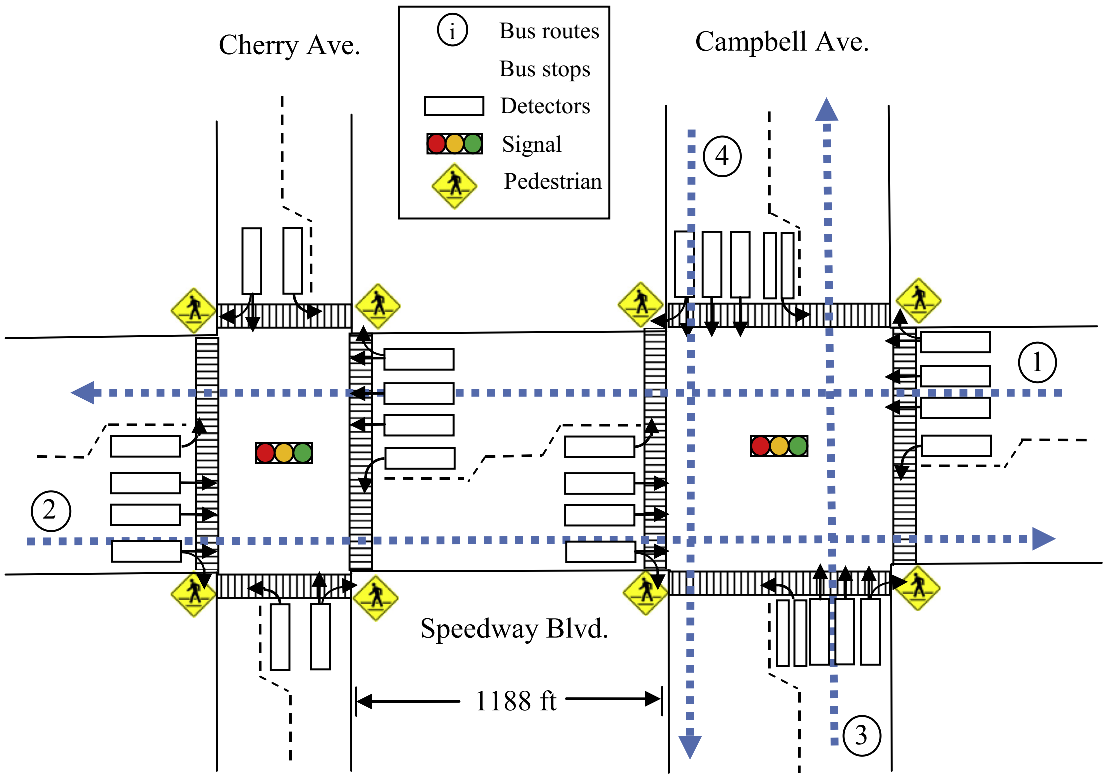

Fig. 9. Layouts of a two-intersection arterial.

Table 3
Traffic volume (veh/h).

Volume scenario	Intersection	Eastbound				Westbound				Northbound				Southbound			
		L[a]	T[a]	R[a]	P[a]	L	T	R	P	L	T	R	P	L	T	R	P
1	Speedway and Cherry	9	462	28	NA	18	417	14	NA	35	19	42	NA	57	18	20	NA
	Speedway and Campbell	50	397	116	NA	87	335	39	NA	91	216	36	NA	54	243	24	NA
2	Speedway and Cherry	22	1110	68	NA	44	1002	32	NA	93	46	102	NA	138	44	48	NA
	Speedway and Campbell	119	952	278	NA	130	583	58	NA	218	519	86	NA	54	243	24	NA
3	Speedway and Cherry	37	1849	114	NA	74	1670	54	NA	156	76	170	47	230	73	81	NA
	Speedway and Campbell	199	1586	463	NA	349	1339	155	NA	363	864	144	47	216	972	96	NA
4	Speedway and Cherry	37	1849	114	36	74	1670	54	46	156	76	170	47	230	73	81	42
	Speedway and Campbell	199	1586	463	36	349	1339	155	46	363	864	144	47	216	972	96	42

[a] L, T, R and P represent left-turn, through, right-turn and pedestrian, respectively.

omit and force-off) to the ASC/3 SIL, either by National Transportation Communications for ITS Protocol (NTICP) or detector-based logic.

Numerical experiments were conducted on a simple two-intersection arterial model that was based on a short section of Speedway Blvd. in Tucson, AZ, bounded by from Campbell Ave. to Cherry Ave. Four conflicting bus routes were added in the model shown as Fig. 9. There are six bus stops on the bus routes. All of the bus stops are far-side stops. It is assumed that all the buses are behind schedule. So every bus sends a priority request when it approaches an intersection at a distance of 650 feet (200 m). Each priority request contains the predicted arrival time at the stop bar based on the current speed of buses. Pedestrian priority is also addressed in the simulation. We assume that each pedestrian will be able to send requests via wireless communications within 50 feet (15 m) of the intersection. Each intersection includes four pedestrian crosswalks. The pedestrian interval, g_{pk}^{Ped}, includes both "Walk" and "Don't walk" interval times. Pedestrian "Walk" time is assumed to be 4 s, but could be a decision variable and the "Don't walk" clearance time is determined by the intersection width divided by the walking speed of 3.5 feet/s (Federal Highway Administration, 2012).

Table 4
Description of compared different methods.

Methods	Actuated	Bus priority	Pedestrian priority	Signal coordination
ASC coord.	✓			✓
ASC-TSP coord.	✓	✓		✓
Robust priority coord.	✓	✓	✓	✓

Table 5
The timing plan optimized from SYNCHRO (The cycle length is 90 s for Scenarios 1–3, and 130 s for Scenario 4).

Volume scenarios	Intersection	Offset (s)	Split (s)							
			ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_7	ϕ_8
1	Speedway/Cherry	12	–*	50	–	40	–	50	–	40
	Speedway/Campbell	0	18	33	18	21	18	33	18	21
2	Speedway/Cherry	80	–	54	–	36	–	54	–	36
	Speedway/Campbell	0	16	36	14	24	14	38	20	18
3	Speedway/Cherry	21	–	59	–	31	–	59	–	31
	Speedway/Campbell	0	17	33	15	25	14	36	18	22
	Speedway/Cherry	14	–	98	–	32	–	98	–	32
4	Speedway/Campbell	0	30	47	16	37	25	52	18	35

* – Means data not applicable since the intersection is controller with only 4 phases.

Table 6
Measured average delay (s) under each scenario with three different methods.

Bus frequency	Volume scenarios	Measurement	ASC coord.	ASC-TSP coord.	Robust priority coord.
High	1	Cars	12.45	12.10	13.69
		Buses	7.77	8.28	5.07
		Pedestrians	–	–	–
	2	Cars	15.79	15.45	15.49
		Buses	11.68	22.91	8.64
		Pedestrians	–	–	–
	3	Cars	22.37	39.85	24.87
		Buses	14.48	37.69	18.67
		Pedestrians	–	–	–
	4	Cars	28.84	35.39	30.24
		Buses	31.04	37.58	26.72
		Pedestrians	54.36	58.16	47.84
Low	1	Cars	12.88	12.96	13.87
		Buses	13.35	10.11	9.22
		Pedestrians	–	–	–
	2	Cars	15.89	15.50	16.22
		Buses	16.58	9.45	14.53
		Pedestrians	–	–	–
	3	Cars	21.93	26.68	24.11
		Buses	20.14	22.39	21.72
		Pedestrians	–	–	–
	4	Cars	27.99	29.20	31.10
		Buses	33.69	26.57	20.49
		Pedestrians	54.06	54.54	48.97

In this experiment, three coordinated control methods were tested and compared with two bus frequencies and four different scenarios of nominal traffic volume (from low to high), as shown in Table 3. Scenario 3 represents average AM Peak traffic demand, whereas Scenario 1 and 2 contain 25% and 60% of total demand in Scenario 3, respectively. Scenarios 1–3 only consider passenger cars and buses, and Scenario 4 includes pedestrian traffic using the vehicle volume defined in Scenario 3. Three coordinated control methods are compared in the simulation, are summarized in Table 4.

The baseline coordination signal plan is obtained from SYNCHRO 7.0, shown as Table 5. "ASC coord." implements the SYNCHRO coordination plan without priority control using the ASC/3 internal coordinator. The "ASC-TSP coord." includes the ASC/3 internal coordinator as well as the ASC/3 TSP logic that is triggered by bus check-in and check-out detectors. The basic strategies of TSP in ASC/3 SIL include early green (red truncation) and green extension. Note that TSP operates based on a First-Come and First-Serve (FCFS) policy. Only one transit vehicle can modify the timing during any given cycle. The detailed settings of TSP in ASC/3 SIL can be found in Econolite Controller Programming Manual (Econolite, 2009). The "Robust coord." method solves the MILP described in this paper by adding coordination requests in rolling horizon fashion. We assume that

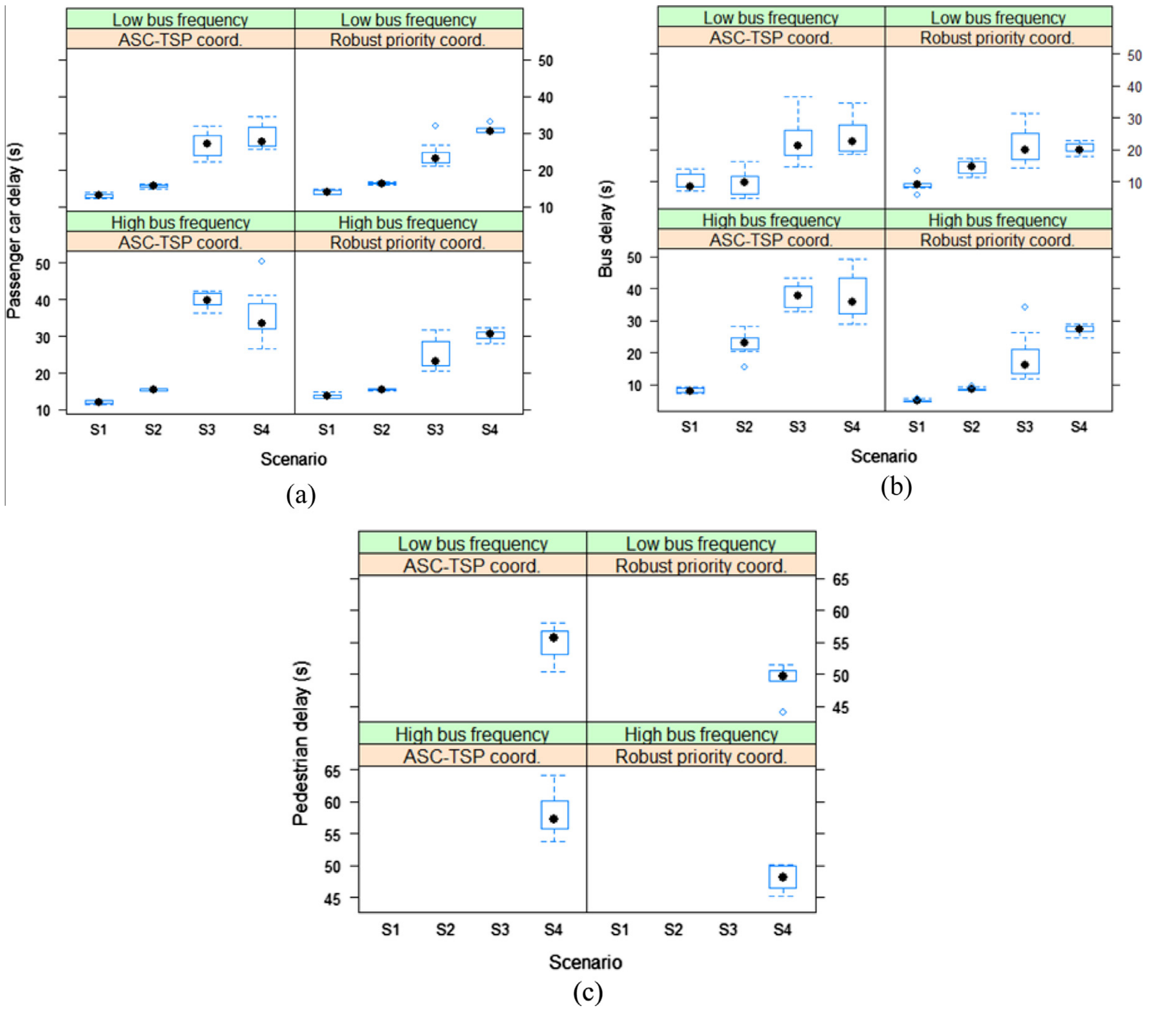

Fig. 10. Box plots of performance distributions of "ASC-TSP coord." and "Robust Priority cood." under different scenarios: (a) passenger car delay; (b) bus delay; and (c) pedestrian delay.

the uncertainty level μ^{λ} is 20%; that is $\lambda_{pk} \in [0.8\lambda^*_{pk}, 1.2\lambda^*_{pk}]$. The weights are chosen to balance delay distributed among passenger cars, buses and pedestrians. Initially we set different weights as $w^P_{mjp} = 1, w^C = 0.5$ and $w^V = 0.001$.

The experiments involve two bus frequencies (3 min headway and 10 min headway) under three different traffic demand volumes. A total of eight scenarios are compared using the three different control methods. In each scenario, the simulation is replicated using ten different random demands in VISSIM.

The measured average delay under each scenario is presented in Table 6. Average delay of each mode is measured under each of the different scenarios. Fig. 10 shows box plots that illustrate the variability for each control strategy, for each mode, across the different traffic scenarios. Several observations from the experimental results are summarized in the following remarks:

1. "ASC coord." holds the lowest average delay for passenger cars, since it does not consider any priority requests. Also it achieves the lowest average bus delay under high volume scenarios (Scenario 3) with high bus frequency. This phenomenon indicates that granting high frequency transit priority will not only disrupt signal coordination, but also increase the delay for other buses.
2. Compared with "ASC-TSP coord.", "Robust priority coord." also shows better performance under simulation Scenarios 1-3, shown as Fig. 10(a)–(c). Under low bus frequency, "Robust priority coord." has similar performance as "ASC-TSP coord.", but with lower variability. In high bus frequency, "Robust priority coord." produces substantially less delay than "ASC-TSP coord." across different traffic modes, especially with high traffic volume. Moreover, "Robust priority coord." deliveries more stable results than "ASC-TSP coord." across most scenarios.

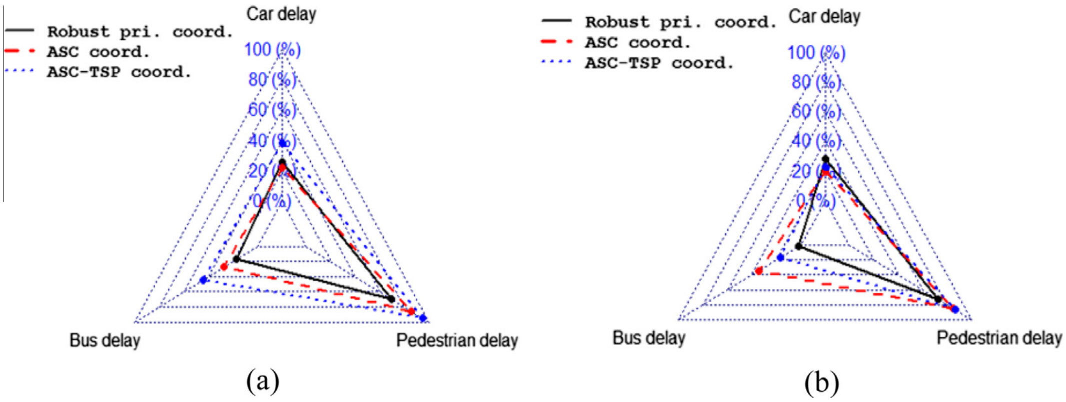

Fig. 11. Radar charts of multi-modal delay of three methods under Scenario 4. 0–100% represents 20–60 s delay: (a) high bus frequency; and (b) low bus frequency.

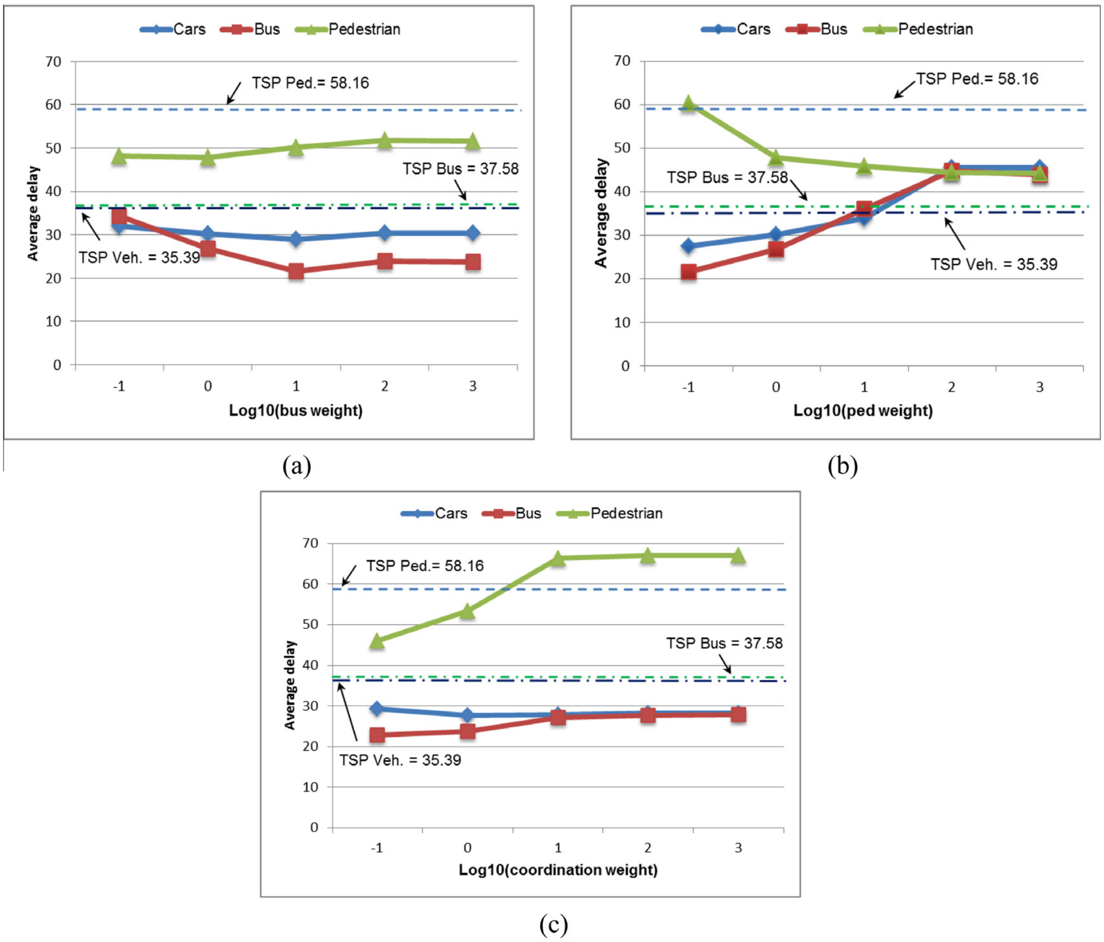

Fig. 12. Multi-modal performance under different weights: (a) changing bus weights from 0.1 to 1000; (b) changing pedestrian weights from 0.1 to 1000; and (c) changing coordination weights from 0.1 to 1000.

3. Multi-modal delay in Scenario 4 is presented in radar charts, shown as Fig. 11(a) and (b). Neither "ASC coord." nor "ASC-TSP coord." optimizes control strategies for pedestrians. In contrast, "Robust priority coord." decreases bus delay by 25.9% and pedestrian delay by 14.0%, with similarly efficient results for passenger cars.

The impact of the weights in the objective function is studies by starting with $w^{P}_{mjp} = 1$, $w^C = 0.5$ and $w^V = 0.001$ and conducting a sensitivity analyses by changing the pedestrian weight, bus weight and coordination weight, respectively. The sensitivity analysis is conducted using Scenario 4 with high bus frequency. Fig. 12(a)–(c) display the sensitivity results. The bus delay can be reduced significantly when the corresponding weight increase from 0.1 to 10, but there is not much benefit beyond 10. It suggests setting the priority weight to 10 while keeping the weight of the other modes at 1 if one traffic mode is preferred. Pedestrian weights could be significantly increased during planned special events, when the pedestrian volume is very high (Ding et al., 2014). We also found that a high coordination weight may cause some adverse impact to buses and pedestrians, whereas the average passenger car delay is not significantly improved, indicating that the coordination weight should remain below 1. Head et al. (2013) has shown that the Pareto frontier of proposed multi-objective optimization model is composed of a discrete number of non-dominated points. The performance of the optimization model will keep constant until the weights reach beyond certain critical values.

5. Conclusion

The multi-modal traffic signal priority control problem is examined in this paper under the assumption that v2i communication is available for different traffic modes. Given the current priority request information, "robust" and responsive priority policies are able to resolve the conflicting issues between multiple priority requests and real-time passenger car actuations, as well as signal coordination, from a system optimum prospective. Not only are the multi-modal priority requests solved with less delay, but the vehicle actuations and signal coordination features are also taken into account. The proposed approach is compared with state-of-practice coordinated-actuated traffic signal control with Transit signal priority (TSP) over several scenarios. For scenarios with high traffic volume, the numerical experiments show that the proposed policy reduces bus delay by 24.9%, pedestrian delay by 14%, while still providing similar passenger car delay, and achieved real-time actuated control, when compared with state-of-the-practice coordinated-actuated signal control with transit signal priority (TSP).

Recently, the proposed decision framework for multi-modal multi-priority control has been successfully implemented in a real-world arterial, composed of six intersections in Anthem, Arizona (Ding et al., 2013). The successful field test demonstrated the promising potential for safe and efficient multi-modal traffic signal operations. In future work, one may consider multi-modal signal control which includes more online sources, such as real-time GPS data from passenger cars.

Although the numerical example in the paper only considers three modes, passenger cars, buses and pedestrians, other traffic modes, including emergency vehicles, railway crossing, trucks, and bicycles could be considered in a similar manner. Emergency vehicles and railway crossing own the highest priority in the formulation. Trucks may require a minimal number stops in order to reduce the emissions and fuel consumptions. Special coordination requests may be generated in favor of truck movements. We can consider bicycles in the same way as pedestrians, or as slowly moving vehicles.

The selection of the weights for each mode, coordination, and actuation flexibility remains an interesting and open area of investigation. Can these weights be selected to achieve an operating policy that allows an operating agency to decide on which mode can receive priority in desired corridors? Preliminary results indicate that the weights can be used to implement a policy, but understanding how operating agencies could specify the weights is an interesting research question.

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