Signalized corridor management with trajectory prediction and optimization under mixed-autonomy traffic environment

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Introduction

Traffic signal control is critical to urban signalized corridor management, and the emerging connected and automated vehicle (CAV) technologies offer new opportunities to the management. Through communication and advanced sensing capabilities, CAVs can detect dynamic surrounding traffic environments and share real-time vehicular information. Their trajectories can be precisely controlled. This study proposes a framework of signalized corridor management with vehicle platooning and trajectory prediction and optimization (SCoPTO) using CAV technologies: the major road platoons can request green time extensions to reduce unnecessary stops; the vehicular trajectories of CAVs are optimized; and CAV platooning operation is implemented such that CAVs can pass the intersection efficiently.

Methodology

An algorithm of trajectory planning with piecewise polynomials (TP3) is applied and enhanced on the basis of our previous work (Zhou, Li, and Ma 2017; Ma et al., 2017; Guo et al., 2019), and it is used to efficiently construct and predict vehicular trajectories for both CAVs and conventional human-driven vehicles (HDV). To form, maintain, and disperse CAV platoons, a platooning operation algorithm is introduced, adapted from the PATH CACC algorithm (Shladover et al. 2014). Then the logic of SCoPTO is described by combining the two CAV applications and signal green time extension at the infrastructure side.

Trajectory planning with piecewise polynomials (TP3)

The TP3 algorithm (Zhou, Li, and Ma 2017; Ma et al., 2017; Guo et al., 2019) provides an analytically solvable operation for kinematically feasible vehicular trajectory construction of CAVs. It is also used to prediction human trajectories when they interact with CAVs. The TP3 algorithm contains two main processes: forward planning (FP) and backward planning (BP). For the FP process, a candidate trajectory is built by applying minimum safety constraint. If the subject vehicle exits intersection during the red phase, the BP process will be activated. The BP attempts to optimize the trajectory from the next start of green phase (boundary condition) and smoothly merge the last part of trajectory with into the FP trajectory, to comsruct a feasible complete trajectory. The trajectories of conventional human-driven vehicles (HDVs) can be also constructed by TP3 using calibrated simplied TP3 behavior, but will not be optimized due to the nature of human drivers.

Platooning

This platooning control logic involves two main following behavior/modes: Adaptive Cruise Control (ACC) mode and vehicle cooperative platooning (similar to Cooperative Adaptive Cruise Control (CACC) mode introduced in Shaldover et al. 2014 and Liu et al. 2018), the use of which depends on the preceding vehicle's type. As shown in **Figure 1**Error! Reference source not found., if the preceding vehicle is a human-driven vehicle (without communication capability) or there is no vehicle in front of the subject vehicle (CAV), the subject vehicle will switch to the ACC mode to regulate the following behavior.

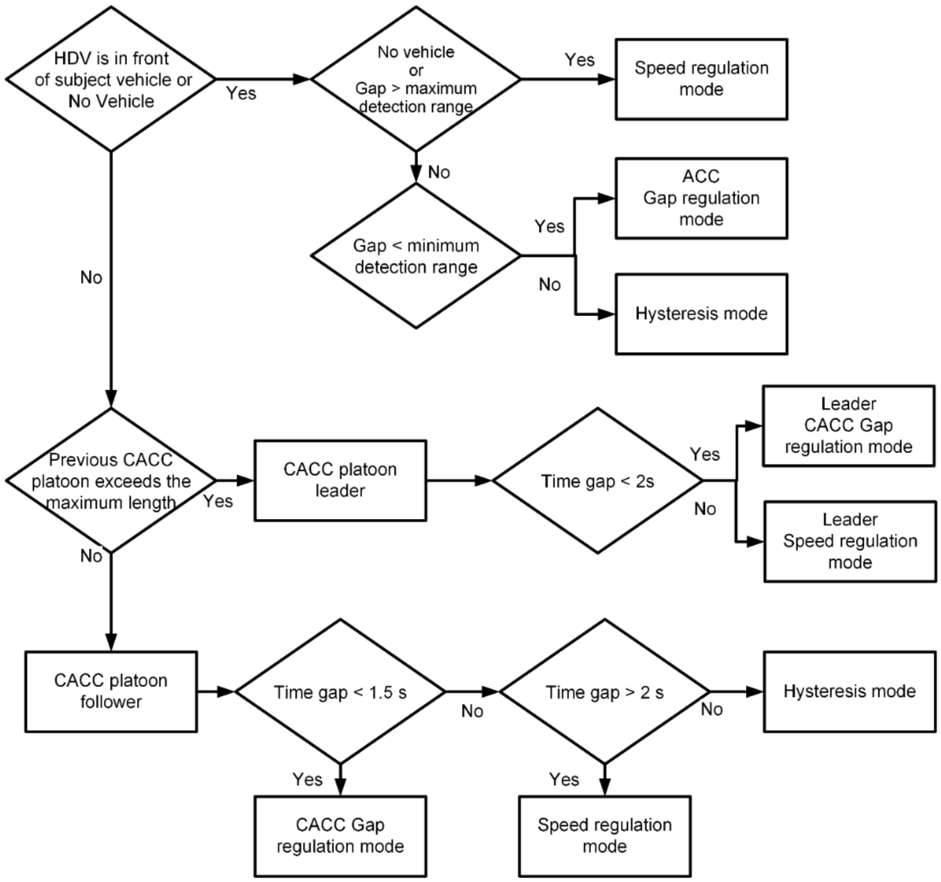


Figure 1. Illustration for platooning operation

If the preceding vehicle is a CAV, the subject vehicle will switch to cooperative platooning mode and communicate with the preceding vehicle to stably follow the preceding CAV with intra-platoon gap (0.7 s in this study) or the inter-platoon gap (1.5 s). The forward collision warning algorithm (Kiefer et al. 2003) is included in the platooning operation.

The platoon split operation is involved in the cooperative platooning control, the immediate following CAV of the departure/cut-in vehicle will become the leader of a new platoon. The platoon split operation can be also activated by cooperative operation command. The lane change behavior is assumed to be the same as HDVs.

Prediction and Control logic of SCoPTO

The main idea of the SCoPTO framework is to let the imminently arriving platoons on the major road cross intersections without stops. For this purpose, the application can simultaneously extend the green phase, control CAV trajectories (which then influences HDV behaviour), and organize vehicle in cooperative platoons. The detailed control logic of SCoPTO is described below:

(1) At each pre-defined time interval, the platoon leader will collect platoon vehicular information and send to the signal controller.
(2) Based on the information set I_n^t, the FP is applied to construct candidate trajectories sequentially.
(3) If the entire platoon P exits the intersection without violating the green time exit constraint, then their trajectories will be accepted. Otherwise,
    (a) P can exit the intersection by extending green time: the platoon keep its current speed until it exits the intersection.
    (b) A portion of the P can exit the intersection by extending green time: a platoon-split algorithm is implemented by internal cooperation within the platoon; the new leader of the second portion of the platoon will follow the optimized trajectories planned by BP.
    (c) P cannot exit intersection within the extended green time: P will follow the optimized trajectory planned by BP, which let the new, smaller, platoon to slowly come to a stop.
    (d) The vehicles at the intersection will be re-grouped into larger platoons to ensure the maximum green time use (i.e. capacity).
(4) Implement the updated signal timing plan.

Simulation Results and Analysis

A realistic simulation network of a signalized corridor with three intersections is used. The speed limit of the corridor is 80 km/h (50 mph) and is 56 km/h (35 mph) for minor roads. Each lane has a detector at upstream of the stop bar to detect HDVs. The corridor demand is set to 2,200 vphpl and 10% of the corridor traffic will turn left at each intersections. The traffic demand for the minor road is 200 vphpl. An optimized fixed signal timing is applied as benchmark. The cycle length is 120 seconds and the maximum green extension set as 10 seconds. Two performance measurements are used in this study: network throughput and average delay.

There are also three additional scenarios:

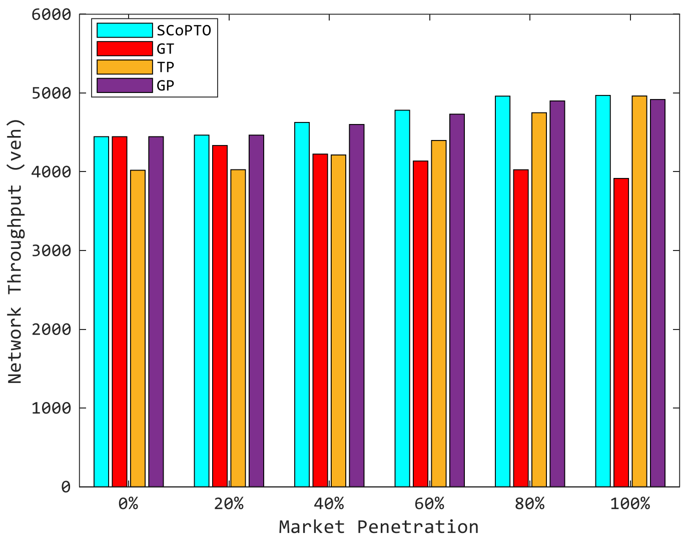
(1) GT: green time extension with trajectory optimization;
(2) TP: trajectory optimization with platooning;
(3) GP: green time extension with platooning.

Figure 2 shows the network throughput and average delay results under different scenarios and market penetrations As shown in **Table 1**, SCoPTO increases 11.7% of the network throughput and reduces 75.4% of the average delay in full-autonomy environment when compared with the benchmark.

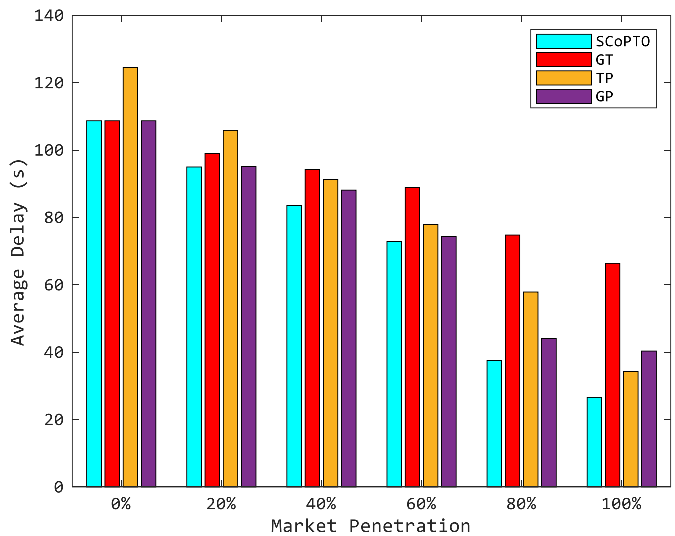
TP performs worse than SCoPTO in terms of the average delay. This is because the green time extension is not applied in TP, and arriving platoons on the major road always need to wait for the next green phase.

The average delay of GP is far above SCoPTO, a difference of 51.26%. This comparison indicates that the trajectory optimization can significantly reduce the average delay. TP3 optimizes the vehicular trajectories to eliminate the conventional start-up lost time and maximize the utilization of the green time.

Interestingly, in the GT scenario, the network throughput is lower than the benchmark case, and the average delay is still higher than any other strategy. This is mainly because GT does not implement the platooning operation, and all CAVs keep the inter-platoon gap, much larger than the intra-platoon gap, and the capacity of the network is wasted. Another important reason is that the desired following gap of the human-driven vehicle (0.9 seconds in this study) is smaller than the inter-platoon gap.



(a) Network Throughput



(b) Average Delay

Figure 2 The throughput and average delay results for different scenarios

Table 1. Benefits with the increase of market penetration (changes calculated as compared to 0% for each strategy)

MP	SCoPTO		GT		TP		GP	
	Network TH (veh)	Changes (%)	Network TH (veh)	Changes (%)	Network TH (veh)	Changes (%)	Network TH (veh)	Changes (%)
0%	4445	0.00	4445	0.00	4019	0.00	4445	0.00
20%	4465	0.45	4333	-2.52	4026	0.17	4465	0.45
40%	4626	4.07	4224	-4.97	4213	4.83	4600	3.49
60%	4781	7.56	4136	-6.95	4397	9.41	4731	6.43
80%	4960	11.59	4025	-9.45	4749	18.16	4899	10.21
100%	4969	11.79	3915	-11.92	4962	23.46	4917	10.62
MP	SCoPTO		GT		TP		GP	
	Delay (s)	Changes (%)	Delay (s)	Changes (%)	Delay (s)	Changes (%)	Delay (s)	Changes (%)
0%	108.67	0.00	108.67	0.00	124.54	0.00	108.67	0.00
20%	94.98	-12.60	98.95	-8.95	105.88	-14.98	95.08	-12.51
40%	83.51	-23.15	94.28	-13.25	91.24	-26.74	88.12	-18.91
60%	72.88	-32.94	88.94	-18.16	77.92	-37.43	74.34	-31.60
80%	37.53	-65.46	74.77	-31.19	57.86	-53.54	44.11	-59.41
100%	26.62	-75.50	66.41	-38.89	34.22	-72.52	40.34	-62.88

* MP = Market Penetration

** Network TH = Network Throughput

Discussion and Conclusion

CAV technologies have the potential to further improve roadway capacity and travel reliability in the future. At the signalized corridors, various CAV applications can be combined with the signal control strategies to maximize traffic efficiency. Based on the simulation results, multiple key observations and implications are summarized as follows:

- The SCoPTO can significantly improve traffic performance in terms of delay and network throughput across all CAV market penetration rates.
- Platooning is the most effective individual operation because it directly reduces the gaps between vehicles, and the benefits is significant even at low CAV market penetration rates.
- Green time extension, as an infrastructure strategy, benefits the traffic system performance the most at lower CAV penetration rates.
- Trajectory optimization can improve traffic performance, especially in the delay reduction and the effect is more significant at higher CAV market penetration rates.

Acknowledgments

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