Simulation-based Comparisons of Signalized and Signal-free Intersection Controls under Connected and Automated Environments

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Introduction

With the rapid development of artificial intelligence and wireless communication, the connected automatic vehicle (CAV) technology is considered as one of the most promising fields in future transportation. CAVs are able to interact with other vehicles on the road as well as roadside facilities, figuring out improved driving trajectories to minimize travel delay and fuel consumption. Also, beneficial from the sensors installed onboard, vehicles could make decision much more effectively, which allows CAVs to maintain a shorter headway. With all the desirable characteristics above of CAVs, the form of traffic organization, especially at intersections which are commonly regarded as the bottleneck of urban traffic, might experience revolutionary changes in the coming years.

An intuitive idea is to replace the traffic lights with a centralized traffic manager. With all the CAVs tracked, the manager could arrange a precise trajectory for each vehicle, including the time and the velocity at which the vehicle should cross the intersection. Without the limitation of traffic lights, CAVs would probably receive a non-stop trajectory with negligible delay, thus considerably enhancing the intersection traffic efficiency. On the other hand, signalized intersection control could also be promoted by the autonomous driving technology. The traffic control center could ensure all the vehicles to pass through the intersection in the maximum allowable speeds during the whole green light duration, which reduces the phase transition losses, and as a result the cycle length can be largely cut down.

Although some existing studies have conducted comparisons between the above two types of intersection controller, the completeness of these comparisons is questionable. Most previous studies failed to consider the usage of CAV technologies to improve the performances of signal control, which to some extent underestimate its potential. In addition, existing comparisons are undertook mostly under limited traffic scenarios, which is incapable of generating reliable conclusions.

Methodology

In this study, we conduct some simulation experiments under various traffic demand patterns to fairly compare the performance three intersection control models under a pure CAV environment. All the environment factors, including the safety buffer, detection range and speed limit, are set as

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the same in all three models to ensure that they are equally benefited from the autonomous driving technologies.

Firstly, we discuss a reservation based non-signal control, which follows *First Come First Serve* (FCFS) principle proposed by Dresner and Stone (2008). The model allocates and reserves feasible trajectories for vehicles exactly in the order of arrival. In the FCFS model, the intersection is divided into multiple tiles, so that the occupation of road space can be equivalent to the occupation of tiles, which reduces variables used to describe the state of the intersection. This method is computational cheap, but might lead to higher delay due to its inappropriate usage of the space-time resources of the intersection.

An improved non-signal control is the rolling horizon conflict-point model proposed by Levin and Rey (2017). This method considers the collision-free conditions in all conflict points, by which the controller formulates a mixed integer program (MIP) to solve the optimal trajectories for a set of vehicles within a certain time horizon. Larger time horizon contributes to lower delay of the involved vehicles, but resulting of the exponentially increasing computational complexity of the MIP. As a consequence, when the traffic volume is large, the intersection performance under the conflict-point-based optimization control will be compromised.

The third comparison in this study is the fixed-time signal control. In this control, the intersection manager firstly find out the earliest feasible time for each vehicle to enter the intersection under the constraints of the vehicle speed and the signal plan. Then, the center focuses on optimizing the vehicle trajectories in the pre-intersection segments to make sure the vehicles arrive the intersection at the highest speed. The trajectory adjustment method adopted in the control is proposed by Zhou et al. (2017) and Li et al. (2018). Meanwhile, the signal timing and cycle length are optimized given the traffic demands to minimize the average vehicle delay.

By setting heterogeneous intersection scenarios, we assess the model performances under different traffic demand patterns and intersection structures. We first test them in a symmetry 4-branch intersection. Then, two branches from the opposite direction are narrowed as secondary roads. As well as the 4-branch intersection, the performance in a T-type junction is tested. In each intersection structure, we run the simulation in both balanced and imbalanced traffic demands. Also, we explore the possible impact of non-homogeneous vehicle arrival sequences. In each scenario, experiments with a total traffic volume from 360 to 14,440 vehicles per hour are conducted. Fig. 1 illustrates the three compared intersection structures.

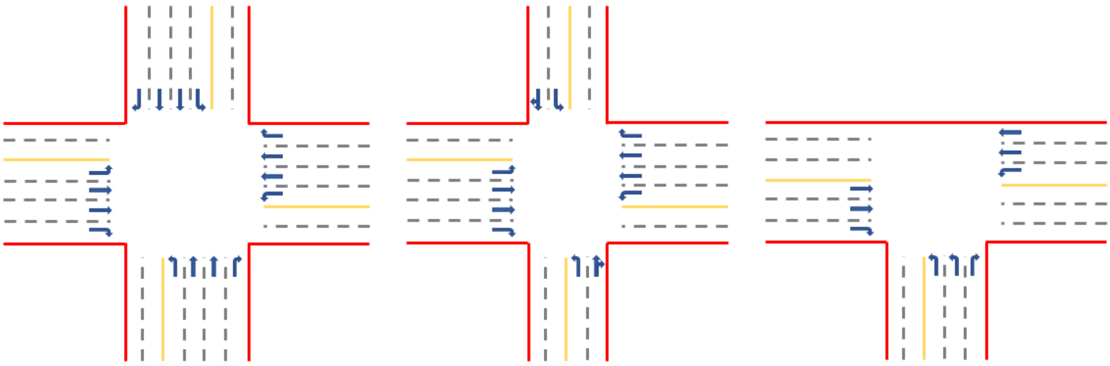

Figure 1. The compared intersection structures

Results

The results show that both non-signal control perform pretty well in low traffic demand scenarios. Among the three controls, the conflict-point model performs best due to its ability to foresee the vehicle arrival within a time horizon. Since the phase transition loss in the signalized control reduces the effective green durations, the control has the highest average delay, but the delay is only a few seconds.

Nevertheless, when the arriving rate gets higher, the queueing length in the two non-signal control models increases infinitely, which indicates the signal-free controls cannot handle excessive traffic demands. The results show that the signalized control has higher traffic capacity. The results suggest that the signalized control makes better utilization of the intersection space-time resources under heavy traffic. Fig. 2 shows the average vehicle delay of the three control in different traffic demand**.**

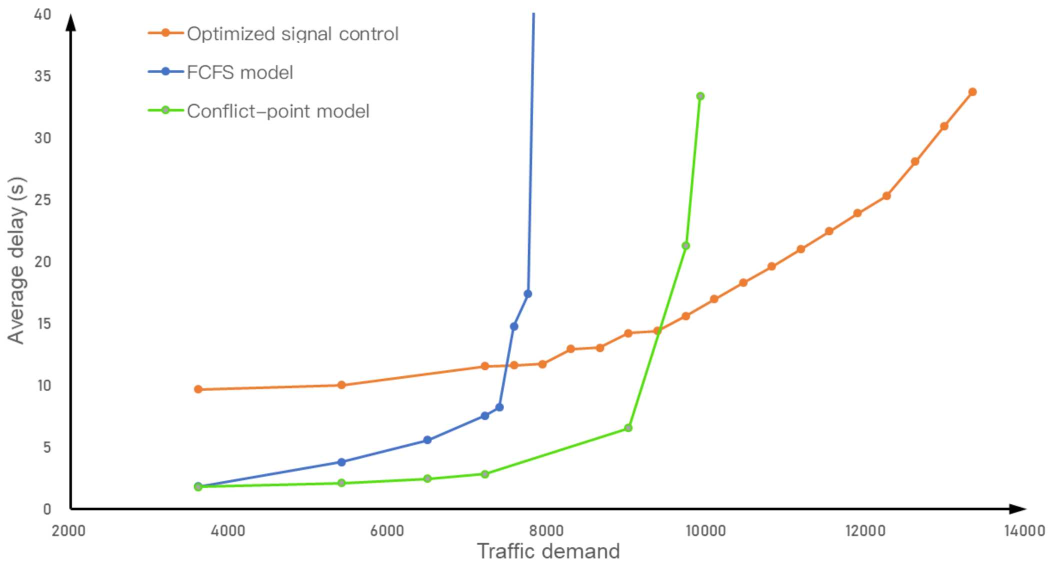

Figure 2. The average delay curve of the three control in different traffic demand

In addition, experiments conducted under heterogeneous traffic scenarios show that the imbalanced traffic demand pattern and the non-stationary arrival sequences have some influence on the model performances, but the general trends maintain the same.

Conclusions

To fairly compare different intersection control schemes in the era of CAVs, this study conducts simulation analyses on three intersection control protocols under heterogeneous traffic demand patterns. The results show that under light traffic, signal-free controls produce lower average vehicle delay; and the capacity of the fixed-time signal control is significantly higher in comparison, indicating that it would be more appropriate to be implemented at busy intersections.

Reference

DRESNER, K. & STONE, P. 2008. A multiagent approach to autonomous intersection management. *Journal of Artificial Intelligence Research,* 31**,** 591-656.

LEVIN, M. W. & REY, D. 2017. Conflict-point formulation of intersection control for autonomous vehicles. *Transportation Research Part C: Emerging Technologies,* 85**,** 528-547.

LI, X., GHIASI, A., XU, Z. & QU, X. 2018. A piecewise trajectory optimization model for connected automated vehicles: Exact optimization algorithm and queue propagation analysis. *Transportation Research Part B: Methodological,* 118**,** 429-456.

ZHOU, F., LI, X. & MA, J. 2017. Parsimonious shooting heuristic for trajectory design of connected automated traffic part I: Theoretical analysis with generalized time geography. *Transportation Research Part B: Methodological,* 95**,** 394-420.