Virtual Platoon-based Vehicle Schedule Optimization Model for Autonomous Intersections

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ABSTRACT

Autonomous intersection control has become a future trend. To solve the problems that the existing reservation-based control model does not globally optimize the vehicle sequence and the low solution efficiency due to model nonlinearity, we propose a vehicle schedule optimization model based on the virtual platoon. Firstly, the distance from the stop line to each interaction point is calculated based on vehicle conflict analysis. Secondly, a virtual platoon is constructed to facilitate modeling. Then, a vehicle sequence mixed-integer linear programming model is constructed with the minimum total delay as the objective and the minimum travel time of vehicles through the control area and the safety interval to reach the boundary of the conflict area as the constraints. Finally, numerical simulation experiments are designed to verify the model's validity, and parametric sensitivity analysis is performed. The results show that the optimization effect of the model under different traffic demands is better than that of the first-come-first-served (FCFS) rule-based model, and the average delay and maximum single-vehicle delay can be reduced by 61.50% and 39.73%, respectively.

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INTRODUCTION

In an intelligent networked environment, vehicles can communicate with each other and execute precise control schemes, achieving non-stopping through signal-free intersections, significantly reducing vehicle delays while maintaining traffic flow continuity. This intersection control mode is called **Autonomous Intersection Control (AIC)**.

The current AIC research mainly has the following shortcomings: (i) most of the research is based on FCFS rules, without overall optimization of the sequence of vehicles through the intersection. (ii) Due to the space and time complexity of AIC, most of the existing AIC research is nonlinear optimization problems, which are difficult to solve or less efficient to solve. (iii) Most of the existing studies only focus on the vehicle control strategy without improving the intersection form.

This paper is oriented to free-turning lane intersections in an intelligent networked environment. We constructed a mixed-integer linear programming AIC model for vehicle schedule optimization based on intersection conflict point analysis and virtual platoon idea from an overall perspective. Moreover, the model's validity is verified by numerical simulation experiments, and the effects of different parameter values on vehicle delays are discussed.

METHODS AND MATERIALS

The optimization objective is to minimize the total vehicle delay. Vehicle delay can be defined as the difference between the actual travel time and the ideal travel time through the control area.

The minimum travel time is the lower time limit to ensure that vehicles can successfully reach the boundary of the conflict area. The arrival time interval constraint limits the time interval of vehicles arriving at the boundary of the conflict area to avoid vehicle collision in the intersection. According to the different turning modes, the arrival time interval constraint can be divided into three types: diverging, converging and crossing, and no-conflict.

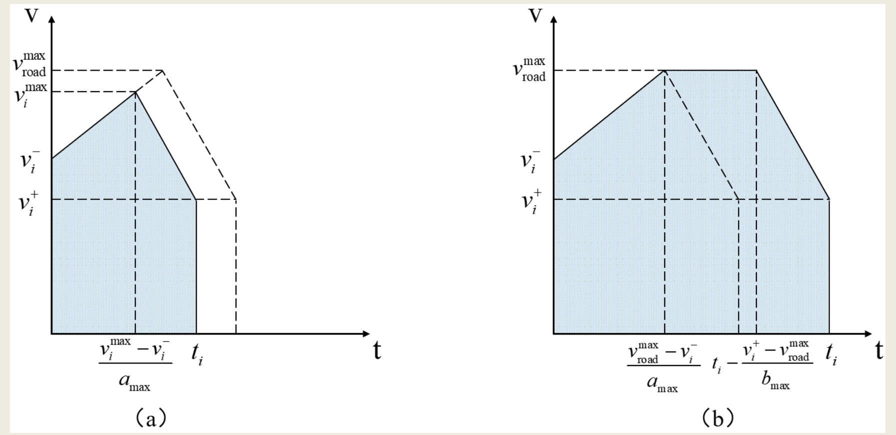


Figure 1. Diagram of the minimum travel time.

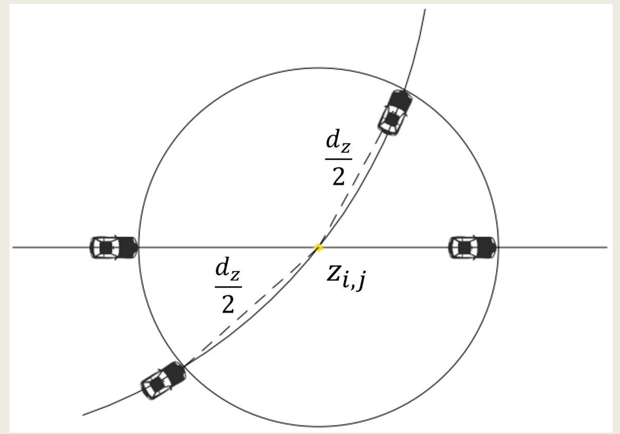


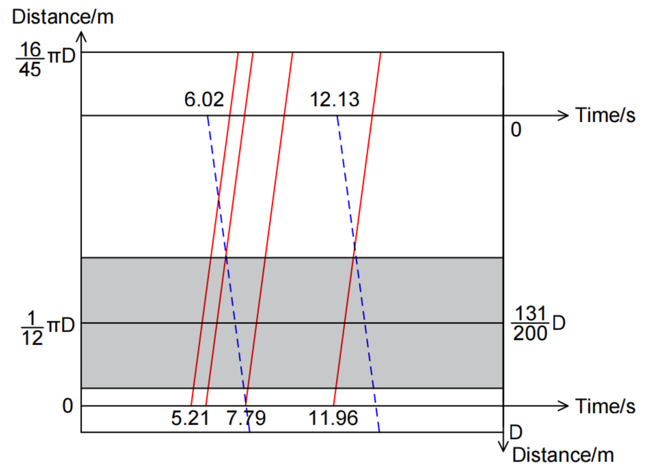
Figure 2. Diagram of interaction region.

RESULTS

Figure 3 illustrates the space-time trajectories of the conflicting vehicles. The solid red lines and the dashed blue lines are vehicle trajectories. The gray area is the interaction region. The existence of boundary points illustrates the model's efficiency for the time of vehicles passing through the conflict area and the space utilization of the conflict area.

Table 1 compares the delay controlled by the proposed model and the FCFS-based model for different traffic demand scenarios. We can conclude that when the traffic demand is low, the continuity between vehicles is poor, leading to a single combination of vehicle passing sequence. Therefore, the optimization ability of the proposed model cannot be reflected. When the traffic demand is high, the change in the sequence of two adjacent vehicles will significantly impact the total delay. At this time, the problem has more room for optimization, and the performance of the overall optimization model can be reflected.

Figure 4 shows the percentage reduction of the average vehicle delay in different traffic demand scenarios and cycle lengths. As the optimization cycle length increases, the effect of the proposed model improves more significantly in the optimal control of vehicle delays.



It can be seen from Figure 5 that the vehicle delay reduction tends to increase as the minimum safety distance and the additional coefficient of interaction area increase. In addition, there are particular values that can minimize the delay without losing the guarantee of safety.

Figure 3. Space-time trajectory of interacting vehicles.

Table 1. Vehicle Delay Comparison of the Proposed Model and the FCFS-based Model.

Scenario	Number of Vehicles	Average Delay of The Proposed Model	Average Delay of The FCFS-based Model	Delay Reduction
1	906	0.21	0.33	37.05%
2	1039	0.27	0.45	40.46%
3	1194	0.32	0.55	42.22%
4	1499	0.47	0.88	46.95%
5	1810	0.74	1.69	55.97%

DISCUSSION

In this paper, a mixed-integer linear programming model is constructed to minimize the total system delay. The overall optimization of the schedule of vehicles passing through the conflict area at an autonomous intersection with free-turning lanes is performed. A virtual platoon is constructed to transform the two-dimensional platoon into a one-dimensional platoon to simplify the modeling process and algorithm. The modeling considers the constraints for vehicles to avoid collision in the conflict area and constrains the minimum time for vehicles to enter the conflict area to avoid abrupt changes in speed and acceleration. In addition, the speed of vehicles entering and exiting the control area is set as variables, which is beneficial for the intersection manager to cope with abnormal situations..

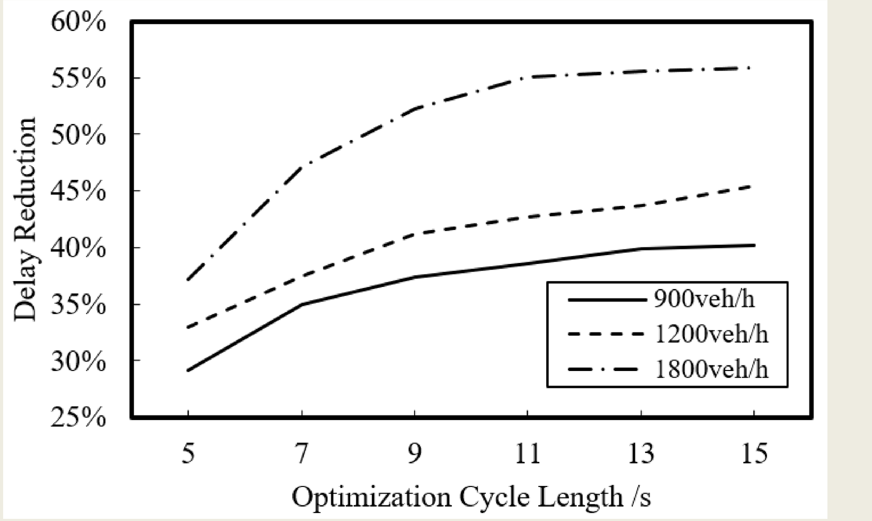


Figure 4. Sensitivity analysis of rolling optimization cycle length.

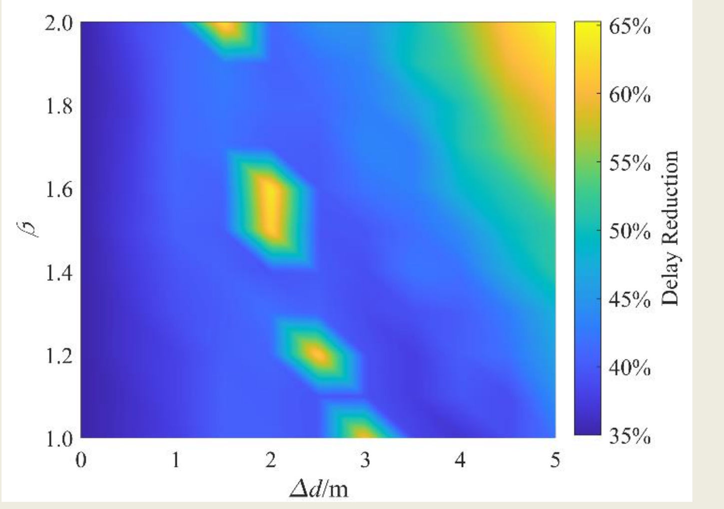


Figure 5. Sensitivity analysis of minimum safety distance and additional coefficient of interaction area.

CONCLUSIONS

(1) The proposed model guarantees the safe crossing of vehicles and reduces vehicle delays significantly.
(2) The length of the optimization cycle has a significant effect on the delay control effect of the proposed model. When the optimization cycle is small, the solution results deviate more from the globally optimal solution.
(3) The vehicle delay reduction tends to increase with the increase of the minimum safety distance and the interaction area additional coefficient.

REFERENCES

1. Levin, M. W., S. D. Boyles, and R. Patel. Paradoxes of Reservation-Based Intersection Controls in Traffic Networks. *Transportation research, Part A. Policy and practice*, Vol. 90, 2016..
2. Yao, Z., H. Jiang, Y. Cheng, Y. Jiang, and B. Ran. Integrated Schedule and Trajectory Optimization for Connected Automated Vehicles in a Conflict Zone. *IEEE Transactions on Intelligent Transportation Systems*, 2020, pp. 1–11. https://doi.org/10.1109/TITS.2020.3027731.