A Two-Stage Optimization Method for Schedule and Trajectory of CAVs at an Isolated Autonomous Intersection

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ABSTRACT

Autonomous intersection management (AIM) has become a state-of-the-art control strategy customized for connected and autonomous vehicles. To address the shortcomings of existing AIM methods, this paper designs an intersection modeling approach and proposes a two-stage optimization method. The modeling approach combines the advantages of tile-based and conflict point-based approaches, considers vehicle shape, and is simple to model. The two-stage method is proposed to reduce vehicle delay and fuel consumption. The first stage is a timing schedule optimization model, assigning vehicle arrival times at an intersection. Based on the output of the first stage, the second stage is a trajectory optimization model, which gives the eco-driving strategies. The two models are both linear and solved by Gurobi. A rolling optimization with variable cycle length is adopted to run the method continuously. Simulation results show that the proposed method outperforms the FCFS-based (first-come-first-serve) method and can reduce vehicle delay and fuel consumption by 81.13% and 33.97%, respectively, under different traffic demands. Sensitivity analyses suggest that (1) a long cycle length is beneficial for the proposed method within certain limits and (2) a proper deceleration within the intersection can balance delay with fuel consumption. In addition, two additional models are compared with the original timing schedule optimization model. It is found that reducing binaries in the first stage can sacrifice the quality of the solution for efficiency, which can be used in conjunction with long cycles.

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INTRODUCTION

Relying on vehicle-to-vehicle and vehicle-to-infrastructure technologies, the intersection manager will take the place of traffic signals and vehicles can intersperse through intersections individually. This control mode is called autonomous intersection management (AIM).

According to the intersection modeling approach, AIM can be categorized as the tile-based approach and the conflict point-based approach. In the tile-based approach, although increasing the granularity improves intersection utilization, it leads to computational challenges. The conflict point-based approach is more amenable to mathematical programming formulations, but it is hard to consider the vehicle's geometry.

As for control policies, the rule-based method outperforms traffic signal control, but generates enormous delays in some cases because of its greedy nature. The optimization-based method bridges the limitations of rule-based methods. However, most of them are computationally challenging.

To address the research gaps, this paper (1) designs a conflict region-based approach that combines the tile-based and conflict point-based approaches. (2) A two-stage linear method is proposed. (3) The proposed method is modified to speed up the solving efficiency.

METHODS AND MATERIALS

We expand conflict points on an infinitely granular grid to a conflict region, resulting in the conflict region-based approach. As a result, we consider vehicle length and width but do not need to add a large number of tiles to the model's constraints.

We propose a two-stage method to optimize timing schedules and trajectories for CAVs at a signal-free intersection with the conflict region-based approach. The first stage, constructed as a MILP, optimizes vehicle schedules. The second stage is linear programming aimed to reduce fuel consumption. Moreover, the model is oriented to free-turning lanes based on the concept that CAVs can reach their destinations without any on-road lane changes to achieve high traffic efficiency and safety.

We redesigned the model's constraints and three MILP models are designed in this study, two of which can obtain optimal solutions and one can obtain suboptimal solutions. The difference between the optimal models is that one incorporates some redundant constraints that do not impact the results to improve the solution efficiency. While for large-scale problems, the proposed suboptimal model can sacrifice a little system optimality in exchange for high-speed solutions.

RESULTS

The proposed method ensures the safety and performs better than the FCFS-based method, reducing delays by up to 81.13% and fuel consumption by up to 33.97%, under different traffic demands (Table 1).

The performance of the proposed method is more stable in controlling delays (Figure 1).

The proposed method can increase the capacity of intersections (Figure 2).

Maintaining the same speed within the intersection as entering the control area reduces delays, but this is not the optimal strategy for eco-driving. A proper deceleration within the intersection can balance delays with fuel consumption and improve the safety of turning vehicles (Figure 3).

The proposed method performs better at longer cycle lengths, but the improvement is no longer significant when the cycle length reaches a certain level (Figure 4).

Setting a suitable threshold to reduce binaries (M3(0)) can speed up the solution to a great extent. Although the quality of the solution is reduced, it is still better than the FCFS-based method (Figure 5).

Table 1. Comparison of Traffic Delays and Fuel Consumption.

Case	Number of Vehicles (veh)	Average Delay (s)		Reduction		Average Fuel Consumption (mL)		Reduction	
		The Proposed Method	The FCFS-based Method	Value (s)	Percentage	The proposed Method	The FCFS-based Method	Value (mL)	Percentage
1	821	0.24	0.41	0.17	41.61%	19.73	20.40	0.67	3.28%
2	1003	0.33	0.62	0.29	46.46%	20.07	21.18	1.11	5.24%
3	1205	0.44	1.04	0.60	57.78%	20.48	22.71	2.23	9.81%
4	1410	0.68	2.07	1.39	66.41%	21.38	26.03	4.65	17.74%
5	1611	0.96	5.43	4.47	81.13%	22.39	34.13	11.74	33.97%

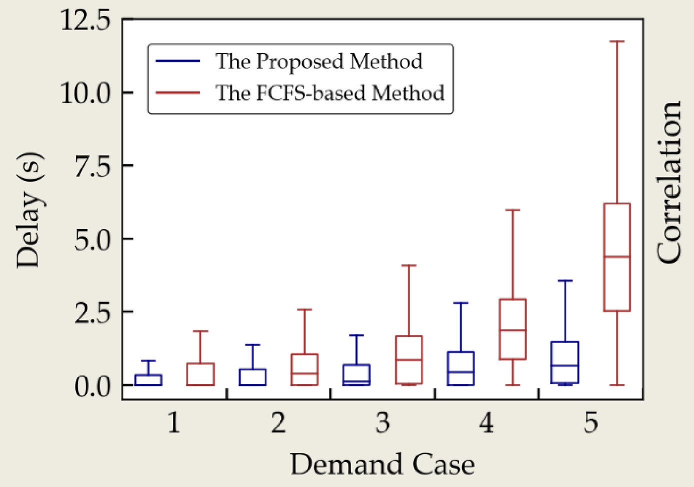

Figure 1. Comparison of vehicle delay.

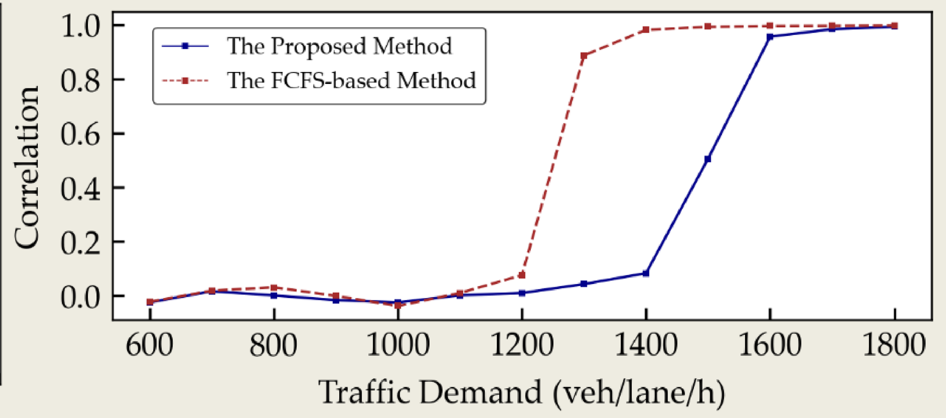

Figure 2. Correlation of vehicle numbers and delays under different traffic demands.

DISCUSSION

The proposed method can deal with the problem from a system perspective, while the FCFS-based method is greedy.

When the cycle length is small enough, the proposed method may degenerate to the FCFS-based method. High-speed driving and frequent acceleration or deceleration will increase instantaneous fuel consumption.

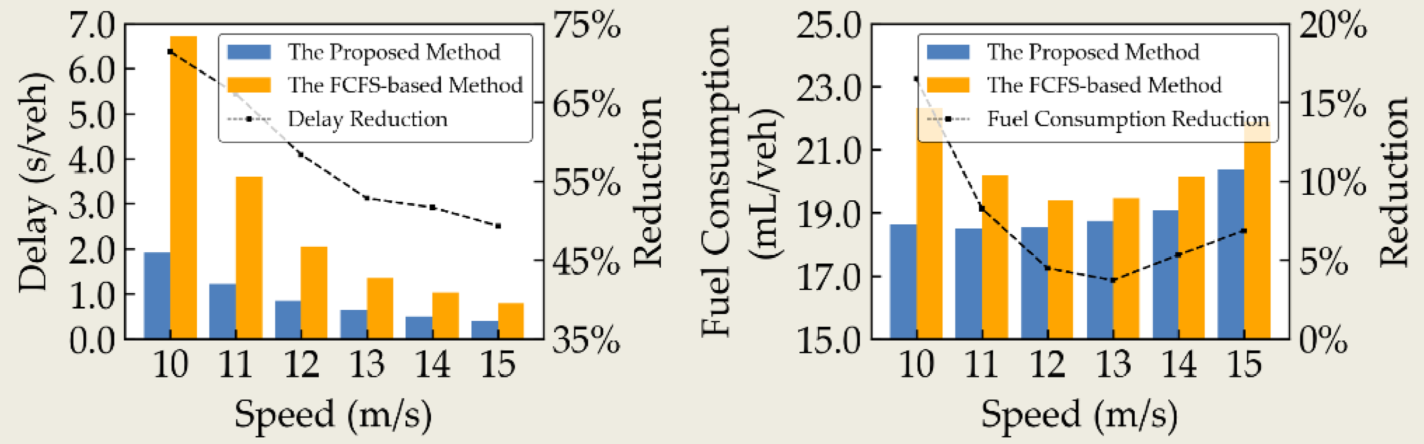

Figure 3. Sensitivity analysis of travel speed within intersections.

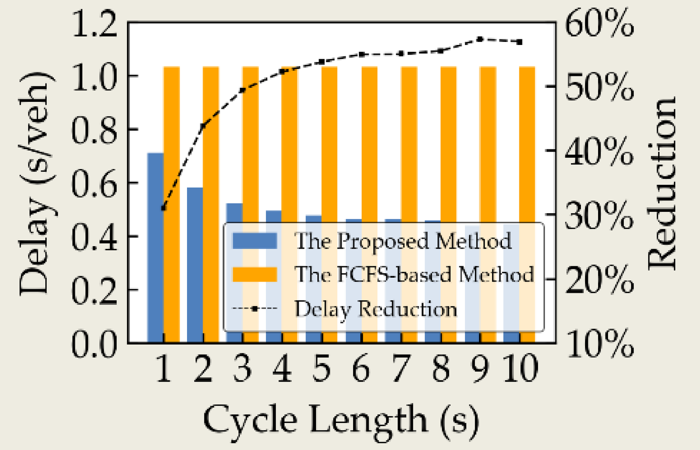

Figure 4. Sensitivity analysis of rolling optimization cycle length.

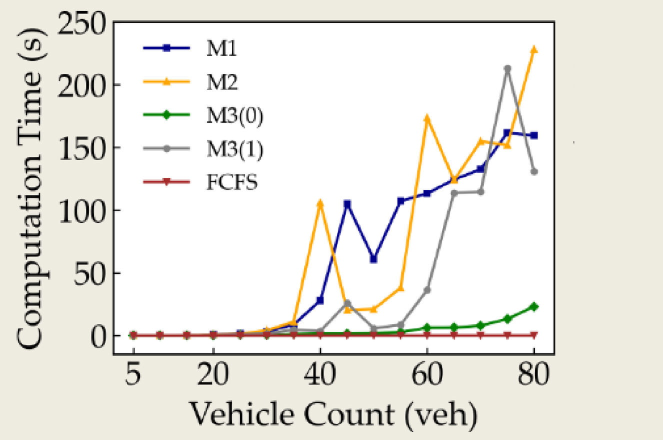

Figure 5. Comparison of different timing schedule models.

CONCLUSIONS

This paper designs an intersection modeling approach, combining the advantages of the tile-based and conflict point-based approach, to consider the vehicle's shape well while maintaining the simplicity of the model. A two-stage method is proposed, considering vehicle delay and fuel consumption. Two additional models are designed to speed up the solution.

REFERENCES

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