Is All-Direction Turn Lane a Good Choice for Autonomous Intersections? A Study of Method Development and Comparisons

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ABSTRACT

Autonomous intersection management (AIM) guides vehicles to pass through signal-free intersections individually. Since vehicles are permitted to turn in any direction from any lane in AIM, it is desired to erase lane changes on the entry lane to achieve high traffic efficiency. However, erasing lane changes exposes intersections to complex conflicts. To study the trade-off between lane changes on the entry lanes and conflicts inside the intersection, this paper makes a comprehensive comparison of two kinds of intersection systems. First, all-direction turn lanes (ADTL) and specific-direction turn lanes (SDTL) are designed to distinguish lane change behaviors. Second, a two-stage model is proposed to manage the oncoming vehicles at the intersection. The first stage is timing schedule optimization and the second stage is trajectory optimization. Then, a method based on Monte Carlo Tree Search (MCTS) is designed to solve the timing schedule optimization model at high traffic demands. Finally, two parts of simulation experiments are conducted in this paper. The first part verifies the performance of the MCTS-based method. The second part compares ADTL and SDTL. The comparisons are conducted in an efficient system and a robust system, respectively. The results show that ADTL outperforms SDTL in the efficient system, but the opposite conclusion appears in the robust system. Therefore, combining ADTL with lane changes may be a good transition, which may even bring out the full value of ADTL.

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INTRODUCTION

Connected and autonomous vehicles (CAVs) offer new ideas for solving intersection problems. CAVs can communicate with other traffic participants in real time and be fully controlled by intelligent agents. Therefore, traffic signals are no longer necessary, replaced by the intersection controller. This type of signal-free intersection is called the autonomous intersection.

Nowadays, some researchers worked on the form of the entry lane at autonomous intersections. They designed all-direction turn lanes (ADTL), where vehicles are allowed to land on any downstream lane from any entry. As a result, CAVs are expected to reach their destinations without on-road lane changes to achieve high traffic efficiency and safety. However, it brings a new problem: while ADTL erases lane changes, they introduce complex conflicts inside the intersection. In contrast, specific-direction turn lanes (SDTL) at traditional intersections reduce conflicts inside the intersection by limiting the flow direction of traffic in different lanes. The trade-off appears here between lane changes on the entry lanes and conflicts inside the intersection. Some scholars may ask, is ADTL better than SDTL at autonomous intersections? To our best knowledge, there is a lack of research on whether the efficiency of the intersection is improved when erasing lane changes.

Motivated by demonstrating an intuitive statistical result, this study conducts a comprehensive comparison of ADTL and SDTL. The contribution of this paper is twofold: 1) A two-stage optimization-based AIM method is proposed, which mitigates the previous drawbacks in which the model is highly nonlinear or contains optimal control. Besides, an MCTS-based method with some heuristic rules is designed for the timing schedule problem with high traffic demands. 2) Comprehensive analyses of different entry lanes are carried out, which brings the ongoing debate on ADTL and SDTL to a broader scene and enlightens us that erasing lane changes may not bring out the full value of ADTL.

METHODS AND MATERIALS

We design two autonomous intersections configured with ADTL and SDTL. Then, a two-stage optimization-based method is proposed to coordinate vehicles to avoid conflicts. The first stage is a timing schedule problem which optimizes vehicle arrivals at the intersection to minimize traffic delay. The second stage plans a superior trajectory for each vehicle to reduce fuel consumption. Besides, an MCTS-based method is designed to handle the timing schedule problem when it comes hard to solve at high traffic demands. Finally, simulation experiments are conducted. We first test the performance of the proposed MCTS-based method. After that, two scenarios, with an efficient system and a robust system, are built to compare ADTL and SDTL.

RESULTS

In an efficient system, ADTL can improve throughput and reduce vehicle delays. Besides, vehicles have smaller travel delays with SDTL under high traffic demand, but the departure delay with SDTL is much larger than that with ADTL (Figure 1).

In a robust system, the intersection throughput is much lower with ADTL than with SDTL. In addition, the saturated flows of intersections in both scenarios are lower than those of the efficient system. Unchanged, the use of ADTL still has lower departure delays because there are no lane change behaviors to impact the traffic flow. However, travel delays are much higher with ADTL than those with SDTL, because more time is required to separate conflicting vehicles in the robust system. In terms of pollution emissions, the CO2 emissions are close in both scenarios, and the reason for such large emissions with ADTL is the result of vehicle delays (Figure 2).

The designed MCTS-based method has the potential to beat Gurobi at high traffic demands. However, when the traffic demand goes down, the MCTS-based methods are no longer superior (Table 1).

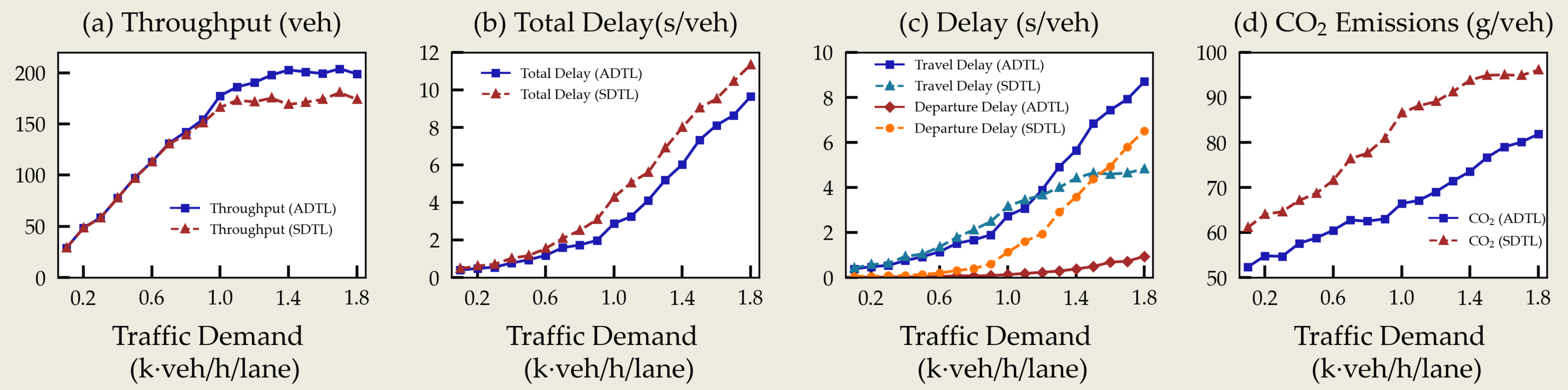

Figure 1. Statistical results of the efficient system.

Table 1. Comparison of Different Methods.

Case	Number of Vehicles (veh)	MCTS-based Method			Gurobi			Difference (s)
		Delay (s)	Iterations	CPU Time (s)	Delay (s)	CPU Time (s)	Gap	
a	141	24.11	1000	20.54	27.31	25	55.60%	-3.20
b	136	22.86	1000	18.38	29.14	20	59.50%	-6.28
c	135	25.67	1000	18.25	27.74	20	56.10%	-2.07
d	103	16.99	1000	10.21	18.26	11	52.90%	-1.27
e1	102	15.07	1000	10.85	14.40	11	52.40%	0.67
e2	102	15.49	500	5.14	16.11	6	57.60%	-0.62
e3	102	16.58	100	1.00	18.15	2	62.60%	-1.56
f1	100	13.60	1000	8.60	13.67	10	47.40%	-0.07
f2	100	13.60	500	4.30	15.07	5	52.30%	-1.46
f3	100	13.68	100	0.89	16.81	1	57.60%	-3.13
g1	67	8.00	1000	4.40	6.94	5	39.50%	1.06
g2	67	8.00	500	2.15	7.22	3	42.90%	0.78
g3	67	8.34	100	0.41	7.65	1	47.40%	0.69
h1	66	7.38	1000	5.09	6.82	6	47.90%	0.56
h2	66	7.50	500	2.54	6.95	3	50.70%	0.55
h3	66	7.53	100	0.49	7.92	1	56.80%	-0.39

DISCUSSION

Reducing the number of conflict points by separating different turnings helps to reduce vehicle delays at unsignalized intersections.

Lane change behaviors taken to separate turnings have a serious negative impact on the subsequent traffic flow.

The efficiency in the CAVs environment comes at the expense of some safety. If we are going to use ADTL without lane changes, we have to make sure that we can control the vehicle with precision. If we want to add some security to the system and allow fault tolerance, ADTL is not a good choice. Therefore, there is a transition in the change from SDTL to ADTL, where the lanes are free-turning, but vehicles can choose whether to make a lane change or not.

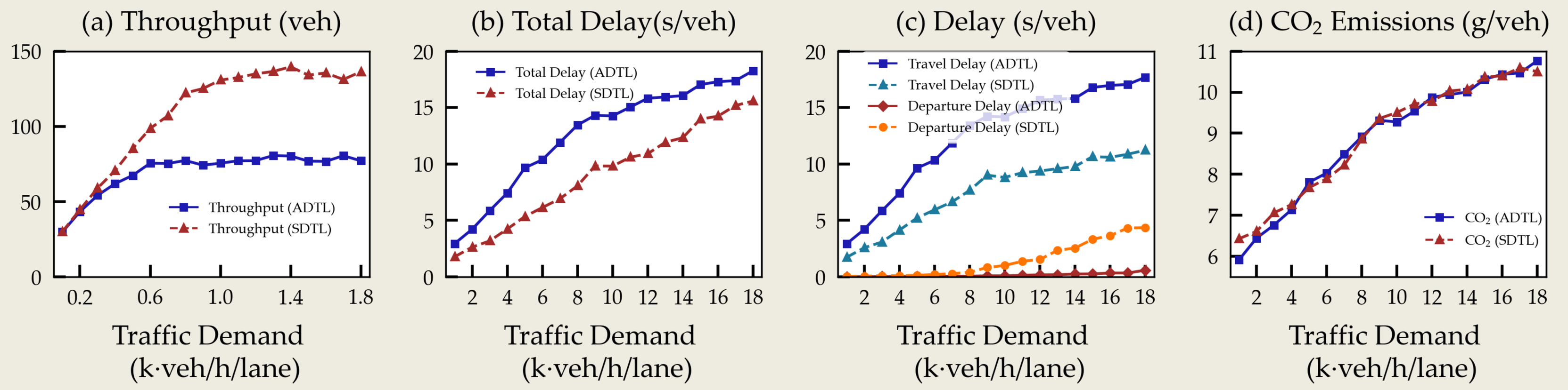

Figure 2. Statistical results of the robust system.

CONCLUSIONS

To help answer the question that whether ADTL is better than SDTL at autonomous intersections, we design two autonomous intersections configured with ADTL and SDTL, and propose a two-stage method to manage the oncoming vehicles. The results show that (1) the MCTS-based method has a great possibility to be superior to Gurobi at high traffic demands. (2) ADTL may generate a large travel delay because of conflicts inside the intersection. SDTL lessens conflicts so that it reduces travel delays, especially at high traffic demands. However, the lane-change behaviors on SDTL have a negative impact on the subsequent traffic, leading to a huge departure delay.

REFERENCES

1. He, Z., L. Zheng, L. Lu, and W. Guan. Erasing Lane Changes From Roads: A Design of Future Road Intersections. IEEE Transactions on Intelligent Vehicles, Vol. 3, No. 2, 2018, pp. 173–184. https://doi.org/10.1109/TIV.2018.2804164.
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.