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The Performance of Connected and Autonomous Vehicles with Trajectory Planning in a Fixed Signal Controlled Intersection

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ABSTRACT

Connected and autonomous vehicles (CAVs) are recognised as a technology trend in the transportation engineering arena. As one of the most popular capabilities of CAVs, trajectory planning attracts extensive attention and interest from both academia and the industry. Segmented trajectory planning is gaining popularity for its simplicity and robustness in computation and deployment. Constructive recommendations and guidelines can be provided by exploring the effects of segmented trajectories in different settings of CAVs and intersections. This research proposes a control strategy for segmented trajectory planning in a fixed signal timing environment. To test the effects of this control strategy, this research designs simplified fixed signalised intersection scenarios and implements segmented trajectory planning features of CAVs with different traffic demand scenarios, distances and speed limits. The results show that the proposed control strategy has stable superior performances in different traffic scenarios especially when the traffic volume is near capacity.

KEYWORDS

connected and autonomous vehicles; trajectory planning; fixed signal-controlled intersection; virtual platoon.

1. INTRODUCTION

Connected and autonomous vehicles (CAVs) are regarded as a promising technology that can alleviate traffic congestion and reduce traffic crashes, which have been the primary research concerns in the avenues of traffic engineers and professionals. Many research topics relevant to CAVs have received extensive interest and investigations, including platooning, trajectory planning, cooperative lane changing, merging and cooperative signal optimisation. Trajectory planning, as one of these research topics, could have important implications on many transportation systems, such as signalised/unsignalised intersections, roundabouts, freeway ramps and freeway segments. It has been proved that trajectory planning can be configured for CAVs to reduce fuel consumption, emissions, traffic delay and travel time along with the consideration of drivers' comfort. With trajectory planning, CAVs can cruise on the road with a speed profile calculated by certain algorithms. With this speed profile, CAVs can achieve minimal travel time, fuel consumption or emission. Also, since safety is always a crucial concern when constructing the trajectories, CAVs are guaranteed with collision-free speed profiles. In deployment, CAVs are also expected to improve safety conditions by reducing accidents caused by human errors.

Considering the computation burden and robustness, segmented trajectory planning is a practical and efficient approach to controlling the CAVs on the road. In segmented trajectory planning, CAVs are assumed to travel along the road with fixed acceleration for each segment of the trajectory. Often the acceleration rate is either the maximum acceleration rate, deceleration rate or zero acceleration rate where CAVs cruise on the road at a constant speed. When travelling through intersections, vehicles can avoid full stops in front of intersections with proper settings.

The previous research of the authors has implemented trajectory planning in an adaptive signal-controlled intersection. However, segmented trajectory planning has not been fully explored in a fixed intersection environment without other external influences. Therefore, in this research, the authors design an empirical arrival time allocation scheme to examine the performance of segmented trajectory planning in different scenarios.

The rest of this paper is organised as follows: first, relevant literature is reviewed and discussed; then the paper presents the methodologies of segmented trajectory planning, arrival time allocation strategy, virtual platoon system, base scenario and simulation settings. Next, this research discusses the simulation results of the proposed control strategy. Lastly, the research findings are summarised in the conclusion section.

2. LITERATURE REVIEW

Trajectory planning strategies have been studied extensively in recent decades. Various optimisation techniques are employed in finding the optimal trajectories in different transportation settings. With the optimisation approaches, previous researchers formulated their trajectory planning problem as an optimal control model or mixed integer programming model. Then certain algorithms were chosen to obtain solutions for these problems. By adding constraints of avoiding collisions, Zhou et al. [1] designed a parsimonious shooting heuristic algorithm for the trajectories of multiple vehicles. Then Ma et al. [2] developed a holistic optimisation model to provide solutions for the optimisation problem established by [1]. Ma et al. [3] later proposed a bilevel optimisation model to optimise CAV trajectories for lateral and longitudinal movements at the same time. Lee and Park [4] constructed a non-linear constraint programming model for the trajectory planning problem of multiple vehicles. In this research, different techniques including genetic algorithm, active set method and interior point method are examined and compared. He et al. [5] developed the optimal trajectories by considering the existing queues in front of the intersection and solved the optimal control problem by the gradient-based metaheuristic methods provided by General Pseudospectral Optimal Control Software (GPOPS).

Besides, it can also be found in the existing literature that traffic signals and vehicles are optimised together. Li et al. [6] proposed an optimisation framework that optimised both traffic signals and vehicles' trajectories at a two-phase controlled intersection. The signal optimisation is implemented by searching all possible phase combinations while the vehicles' trajectories are planned with a different number of segments. The results show that the joint optimisation framework outperforms the actuated signal control under different lengths of communication range, from 500 ft to 3,000 ft. Nevertheless, this study did not examine the effects of signal optimisation and trajectory planning individually, and how much of the improvement is brought by trajectory planning is unknown. Later, the work was expanded by including turning vehicles and employing genetic algorithms to solve the newly developed optimisation problem. All these works have a common assumption of a 100% CAV market penetration rate. Guo et al. [7] developed a combined control strategy for signal timings and vehicle trajectories that can account for mixed traffic volume scenarios.

In addition to the optimisation-based trajectory planning approaches, Feng [8] et al. proposed segmented trajectory planning to minimise travel time and emission simultaneously. In this segmented trajectory planning, the speed profile is largely dependent on the longest travel time and shortest travel time when vehicles implement the maximum acceleration and deceleration rates. Along with this trajectory planning strategy, [8] also developed a signal optimisation strategy with a dynamic programming approach so that the leaders of virtual platoons can be assigned a proper arrival time. Developed from [8, 9] proposed a joint optimisation system for signal control and trajectory planning with a mixed integer linear programming approach. Ding [10] et al. revised the segmented trajectory planning control by removing the deceleration cases due to the assumption that the deceleration cases can cause unstable traffic flow. The argument may be valid when significant traffic volume is present. These two pieces of research are built on a signal optimisation scheme and assume all vehicles can be cleared within each cycle with the help of cooperative signal optimisation. In addition, Pourmehrab et al. [11] developed an optimisation framework for signal timing and mixed traffic of CAVs and conventional vehicles (CNVs). The trajectory of CAVs was optimised through a three-stage trajectory, which is similar to the three-segment trajectory in [8]. The trajectories of CNVs were estimated through the Gipps car-following model. The roadside radar or camera was assumed to be installed to collect the necessary information about CNVs including lane, location and speed.

In previous research, the authors implemented segmented trajectory planning in the environment of unconventional intersection design and did a preliminary comparison with an equivalent conventional intersection [12–15]. It was found that the performance of segmented trajectory planning is inferior compared to platooning and signal optimisation, especially in heavy traffic scenarios. The performance of segmented trajectory planning is even worse in consecutive intersection scenarios. However, the findings of previous work are the results of the compounding effects of multiple interconnecting factors including turning movement, signal optimisation, platooning control, consecutive intersections and so forth. A further look at the trajectory planning standalone is needed to clarify the effects of segmented trajectory planning in different traffic environments.

By providing the arrival time allocation scheme and final speed determination strategy, this research examines the performances of segmented trajectory planning in a simplified intersection scenario to deliver a closer look without the interference of other parameters. To achieve this end, this research developed an arrival time allocation scheme for signal control. A virtual platoon concept is also established based on the developed arrival time allocation scheme.

3. METHODOLOGIES

3.1 Trajectory planning scheme

The trajectory planning scheme for CAVs is developed based on [8] with justifiable modifications. Generally speaking, there are three segments in total if considering the two-segment trajectory as a special case of a three-segment trajectory. In the first segment, CAVs will first either accelerate or decelerate with maximum acceleration/deceleration capacity; for the second segment, CAVs travel on the road with zero acceleration rate, i.e. constant speed. In the third segment, CAVs will again travel on the road with a maximum acceleration rate or deceleration rate. The only required inputs are the final speed and travel time when CAVs arrive at the intersection.

The transition time steps t_1 and t_2(between the first and the second segment, the second and the third segment, respectively) can be determined given the following equation in the deceleration case ($v_0>v_f$) and acceleration case ($v_0<v_f$), respectively.

$$\frac{v_0+v_c}{2}\cdot t_1+v_c\cdot\left(t_2-t_1\right)+\frac{v_f+v_c}{2}\cdot\left(t_f-t_2\right)=D \tag{1}$$

$$v_c=\begin{cases}v_0-a_L\cdot t_1=v_f+a_L\left(t_f-t_2\right),\ v_0>v_f\\ v_0+a_U\cdot t_1=v_f-a_U\left(t_f-t_2\right),\ v_0<v_f\end{cases} \tag{2}$$

where v_0 is the initial speed at which the vehicle enters the communication range, v_c is the constant speed where the vehicle cruises at the second segment (if there is one), v_f is the final speed at which the vehicle arrives at the intersection, D is the distance toward the intersection, a_L and a_U are the maximum deceleration rate and acceleration rate, respectively.

$$v_0>v_f\begin{cases}t_L=\dfrac{L}{v_0}+\dfrac{\left(v_0-v_f\right)^2}{2\cdot v_0\cdot a_L}\\[2ex] t_U=\dfrac{L}{v_f}+\dfrac{\left(v_0-v_f\right)^2}{2\cdot v_f\cdot a_L}\end{cases} \tag{3}$$

$$v_0<v_f\begin{cases}t_L=\dfrac{L}{v_f}+\dfrac{\left(v_0-v_f\right)^2}{2\cdot v_f\cdot a_L}\\[2ex] t_U=\dfrac{L}{v_0}+\dfrac{\left(v_0-v_f\right)^2}{2\cdot v_0\cdot a_U}\end{cases} \tag{4}$$

An optimal segmented trajectory solution only exists when the vehicle's arrival time t_f satisfies the following requirement expressed in *Equation 5*.

$$t_L\le t_f\le t_U \tag{5}$$

Whether the vehicle should accelerate or decelerate depends on the variables of the target final speed v_f and arrival time t_f. Based on their relationships with the time boundary and current speed, there are six cases in total as follows.

Case 1: when the final speed v_f *is less than the current speed* v_0 *and the arrival time is equal to the lower time boundary* t_L $(i.e.\ v_0 > v_f\ \&\ t_f = t_L)$. CAVs would cruise at the current speed v_0 and decelerate to the final speed with a_L at the last second. In this way, CAVs should arrive at the intersection with an elapsed time of a lower time boundary t_L.

Case 2: when the final speed is lower than the current speed and the arrival time is greater than the lower time boundary and less than the higher boundary $(i.e.\ v_0 > v_f\ \&\ t_L < t_f < t_U)$. In this case, the vehicle can decelerate to a constant speed v_c immediately with a_L. Then CAVs cruise on the road with this constant speed until time t_2. After t_2, the vehicle starts to decelerate again with a_L until arriving at the intersection and reaching the final speed v_f.

Case 3: when the final speed is lower than the current speed and the arrival time is equal to the upper boundary $(v_0 > v_f\ \&\ t_f = t_U)$. In this case, the vehicle can decelerate immediately with a_L to the final speed and cruise with the final speed v_f until arriving at the intersection.

Case 4: when the final speed is greater than the current speed and the arrival time is equal to the lower time boundary $(v_0 \le v_f\ \&\ t_f = t_L)$. In this case, CAVs accelerate immediately with a_U up to the final speed v_f and travel on the road at the final speed until passing the intersection.

Case 5: the final speed is greater than the current speed while the arrival time is larger than the lower time boundary and lower than the upper time boundary $(v_0 \le v_f\ \& t_L < t_f < t_U)$. This means a three-segment trajectory can be applied, in which vehicles can accelerate with a_U to a calculated constant speed v_c and cruise for a period of t_2-t_1, then accelerate again with a_U to the final speed v_f while arriving at the intersection.

Case 6: the final speed is greater than the current speed while the arrival time is equal to the higher time boundary $(v_0 \le v_f\ \&\ t_f = t_U)$. In this case, CAVs cruise on the road with v_0 until t_1. After t_1, CAVs accelerate immediately with a_U to the final speed while arriving at the intersection.

In summary, the first three cases describe deceleration scenarios and the last three cases describe acceleration scenarios. When the arrival time is strictly equal to the time boundaries, then two-segment trajectory planning is applied; when the arrival time falls in between lower and higher time boundaries, then three-segment trajectory is applied. Otherwise, no optimal segmented trajectory exists.

3.2 Determining the final speed

Assuming the arrival time is assigned by the intersection controller, which is illustrated in the following sections, the remaining input for the trajectory planning model is the final speed v_f. Higher speeds are naturally favourable for higher intersection capacity and less traffic delays. The model formulation is constructed in such a way that not all combinations of final speed and travel time can be guaranteed with a solution. Therefore, in this research, we discrete the continuous speed range into an integer speed list, from minimal speed to the maximum allowed speed with an interval of 1. The minimal speed is 1 ms and the maximum speed is the speed limit of the road. CAVs travelling on the road would iterate each potential viable final speed according to the time boundary, then the maximum final speed from the speed list is selected so that the traffic delay is minimised and intersection capacity is improved.

3.3 Arrival time allocation scheme under fixed signal-controlled intersection

With this segmented trajectory planning strategy illustrated above, the inputs are the final speed and arrival time of CAVs at the intersection. The final speed is obtained by selecting the maximum viable speed. In this research, the arrival time of CAVs is allocated by the intelligent traffic signal controller. In ideal condition, the vehicle should be assigned an arrival time as short as possible. The shortest travel time is constrained by the maximum acceleration rate, distance, maximum speed and current speed. The equation for calculating the shortest travel time t^e is illustrated below [10];

$$t^e = \begin{cases} \dfrac{\sqrt{(v_0)^2 + 2a_U D} - v_0}{a_U}, & D < \dfrac{v_{max}^2 - v_0^2}{2a_U} \\ \left(D - \dfrac{v_{max}^2 - v_0^2}{2a_U}\right) / v_f + \dfrac{v_{max} - v_0}{a_U}, & D \geq \dfrac{v_{max}^2 - v_0^2}{2a_U} \end{cases} \tag{6}$$

where t^e is the earliest time for the vehicle to arrive at the intersection and v_{max} stands for the speed limit on the road. After t^e is obtained by the above equation, the signal controller could check whether this t^e is occupied by preceding vehicles. If this t^e is a vacancy, then the vehicle is assigned with the arrival time of t^e, and the trajectory planning control can start generating corresponding trajectories with an arrival time of t^e. With the help of trajectory planning control, CAVs travel through the intersection within two seconds in most cases. Therefore, the intersection controller allocates 2 seconds for each vehicle's arrival, i.e. t^e, $t^e + 1$. Although 2 seconds is sufficient for vehicles passing the intersections, it is still worth noting that the shorter the headway between vehicles is, the more robust the arrival time allocation scheme is. However, if this t^e is occupied by preceding vehicles, then the vehicles should search next available green time slots and occupy the next available green time slots. The pseudo-algorithm is illustrated below to determine the available time slots for CAVs.

```
Initiating the simulation
   Simulation step +1
   Generate the ordered green time slot list $G$ for the target phase based on the signal timing plan of the upcoming intersection
   Iterate all vehicles heading for the target phase in the network at the current time step
   For each vehicle $v$:
     calculate the $t^e$
     Check whether $t^e$ in $G$
       If $t^e$ in $G$:
         Assign the arrival time$t^e$ for the vehicle from the list $G$
         Remove $t^e$, $t^e$ +1 from $G$
       If $t^e$ not in $G$:
         Search the next available green time ($g$) in the green time slot list $G$
         Assign $g$ as the arrival time to the target vehicle $v$
         Remove $g$, $g$+1 from $G$
   If the maximum simulation step reached
     Stop simulation
   else:
     Continue simulation
```

3.4 Virtual platoon

The vehicles that can travel through the intersection within the same cycle are regarded as within the same virtual platoon in this research. The car-following model of vehicles inside a platoon is still IDM. According to the arrival time allocation scheme introduced above, the vehicles that can be assigned to a platoon should satisfy the following requirements in *Equation 7*, which means the vehicles can travel through the intersection within the same phase;

$$abs(g_i - g_{i+1}) \leq p_{target} \tag{7}$$

where g_i and g_{i+1} are the arrival time allocated by the allocation strategy; P_{target} represents the target phase duration and *abs*0 represents the function that returns the absolute value of the difference between two numbers. Due to the virtual platoon concept, the controller only needs to determine the trajectories of the platoon leaders and reduce the computation burden. This operation can also avoid collisions between vehicles while the vehicles are implementing the generated trajectories.

Since the trajectory planning scheme only applies to the platoon's leader, its computation burden is significantly reduced, and the simulation experiments are achievable with a normal personal computer.

3.5 Base scenario

In the base scenario, the authors select the IDM as the car-following logic for CAVs without trajectory planning control. IDM model can output a desired acceleration rate that is free of collision with preceding vehicles. Its parameters are intuitively measurable and allow fast simulation. It is a well-recognised car-following model for CAV-related research [14, 16, 17]. The required inputs of IDM are the velocity of the subject vehicles, the distance between the subject vehicle and the preceding vehicle and the velocity difference between the subject vehicle and the preceding vehicle, as *Equation 8* and *9* show below:

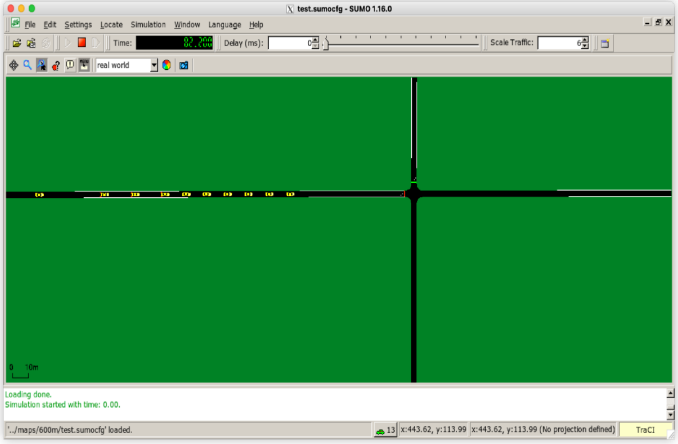
$$a(s,v,\Delta v)=a_m\left(1-\left(\frac{v}{v_d}\right)^{\propto}-\left(\frac{s^*(v,\Delta v)}{s}\right)^2\right) \tag{8}$$

$$s^*(v,\Delta v)=s_0+vT+\frac{v\cdot\Delta v}{2\sqrt{a_m b}} \tag{9}$$

where a represents the acceleration rate; a_m represents the maximum acceleration rates; v indicates the current speed; v_d is the desired speed; Δv stands for the speed difference between the subject vehicle and its preceding vehicle; $\propto$ is the acceleration exponent, set as 4 by default; s is the headway at the current time step between the subject vehicle and its leading vehicle; $s^*(v, \Delta v)$ is the minimum desired headway; s_0 is the standing distance when vehicles stop moving; T is the desired headway and b represents the desired deceleration rate.

3.6 Simulation setting

In this research, SUMO 1.9.1 (Simulation of Urban MObility) is chosen as the simulation platform to examine the control strategies illustrated above. SUMO is a well-recognised and popular microscopic traffic simulation software in the avenues of transportation planning and management science [9, 13, 14, 15]. Considering the drivers' comforts, the value of the maximum acceleration rate and deceleration rate is assumed to be 2 m/s^2 and −2 m/s^2, respectively. The benchmarks for evaluating the performance of CAVs with different controls are average traffic delays (s), fuel consumption (ml) and travel time (s) per vehicle in the network. Traffic delay is defined as the difference between the ideal travel time (vehicle travels through the road network with maximum speed without any interruption by other vehicles or intersections) and actual travel time. The fuel consumption is generated by the internal function inside the SUMO, which is documented in [17]. The actual travel time indicates the time difference when a vehicle is inserted into the network and leaves the network. The road network is designed so that a stream of vehicles from one approach travels through a two-phase controlled intersection without considering the turning vehicles. As shown in the figure below, a stream of vehicles is heading towards the signalised intersection with 42 s green, 3 s yellow and 45 s red.



Time: 82.200

Delay (ms): 0

Scale Traffic: 6

Loading done.
Simulation started with time: 0.00.

'../maps/600m/test.sumocfg' loaded.

13 x:443.62, y:113.99 x:443.62, y:113.99 (No projection defined)

Figure 1 – A stream of vehicles running on the road network in SUMO

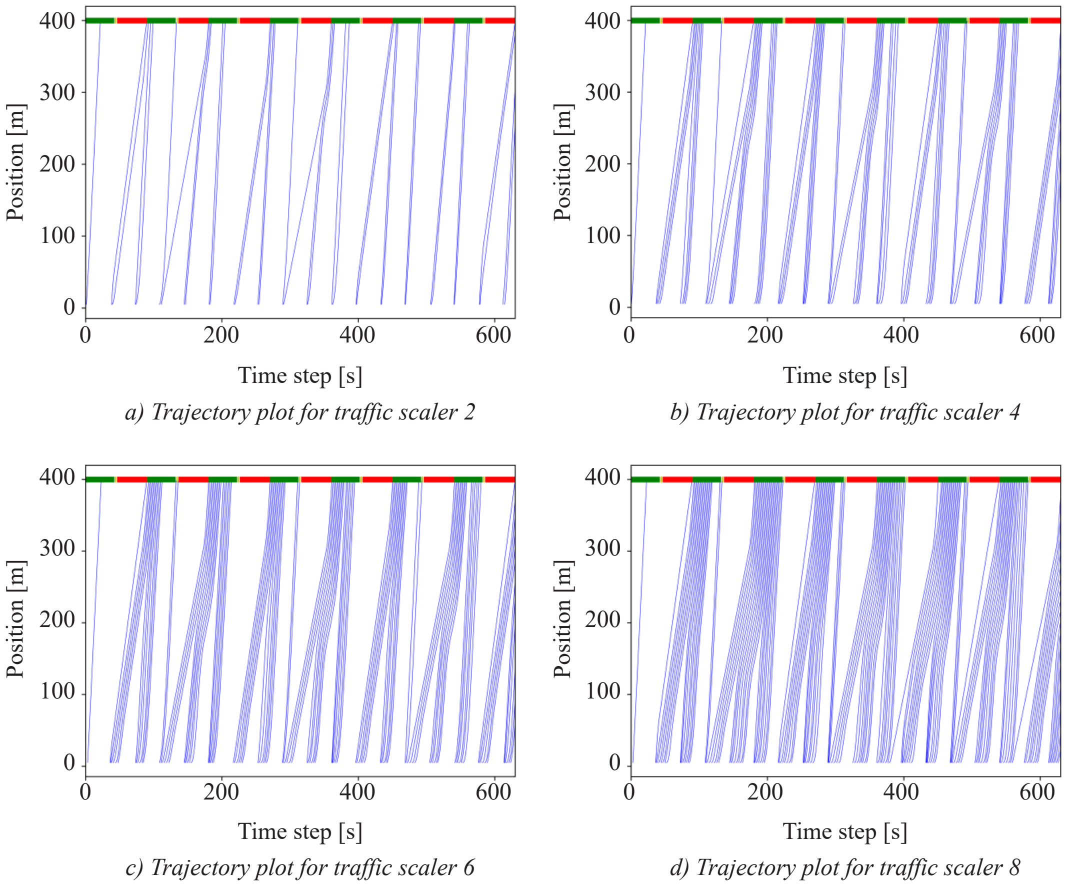
With SUMO, this research has developed various simulation scenarios to examine the performance of trajectory planning control strategies, including different distances, speeds and traffic demand scenarios. The minimum traffic scaler is 1, representing 100 veh/h/lane while the maximum traffic scaler is 8, representing 800 veh/h/lane, which is near road capacity in the designed road network.

4. RESULTS AND DISCUSSIONS

4.1 Effectiveness of trajectory planning strategies with arrival time allocation scheme

Before the examination of the performances of CAVs under different settings, the demonstration of the effectiveness of trajectory planning, arrival time allocation scheme and virtual-platoon concept are implemented in a specified scenario as follows. The communication range between the intersection and vehicles is set as 400 m and the maximum speed is 20 m/s (72 km/h).

The vehicle trajectories of CAVs with trajectory planning control can be found in *Figure 2*. *Figure 2* shows the trajectories of CAVs that can all successfully pass the signalised intersection at the green time in all designed traffic demand scenarios. In light and medium traffic volume scenarios, the final speed is relatively high. When the traffic scales up, the final speed decreases gradually. From *Figure 2* it can also be observed that 800 veh/h/lane is near the intersection capacity as very little green time is vacant.



a) Trajectory plot for traffic scaler 2 *b) Trajectory plot for traffic scaler 4*

c) Trajectory plot for traffic scaler 6 *d) Trajectory plot for traffic scaler 8*

Figure 2 – Trajectory plot for different traffic demand scenarios with a communication range of 400 m and a maximum speed of 20 m/s

Under the same settings, *Table 1* below shows the aggregated measures of the effectiveness of the proposed control (represented by OP in *Table 1*). The results are obtained through 5 random runs with different random seeds and each lasts for half an hour. *Table 1* exhibits that trajectory planning can consistently reduce traffic delays, fuel consumption and travel time. When the traffic volume is larger, the improvement magnitudes are larger. The highest improvement magnitude occurs when the traffic demand is 800 veh/h/lane. At this traffic scaler, the traffic volume is already over-saturated in the base scenarios. When the intersection is over-saturated, the traffic delay, fuel consumption and travel time all increase dramatically. When high traffic volume is present, the improvement is nearly doubled. This is because the trajectory planning control strategy can maximise the utility of green time. For the base scenario where vehicles are running without trajectory planning, many of the vehicles must make a full stop in front of the stop bar of the intersection. Then a significant traffic delay occurred when they accelerated back to their desired speed.

Table 1 – Performances of the proposed control framework compared to the base scenario

	Average traffic delay			**Average travel time**			**Average fuel consumption**		
Scalers	**Differences**	**OP**	**Base**	**Differences**	**OP**	**Base**	**Differences**	**OP**	**Base**
1	-0.5%	13.52	13.58	-0.1%	43.96	44.02	-2.8%	63.52	65.37
2	-3.6%	16.58	17.19	-1.3%	47.02	47.64	-9.5%	64.05	70.76
3	-8.4%	19.09	20.84	-3.4%	49.54	51.29	-14.8%	64.84	76.10
4	-3.9%	22.11	23.00	-1.7%	52.56	53.44	-15.9%	66.77	79.35
5	-11.2%	22.56	25.42	-5.9%	53.01	56.34	-18.8%	66.30	81.68
6	-6.1%	25.59	27.24	-3.3%	56.03	57.94	-19.5%	67.04	83.22
7	-10.2%	27.20	30.29	-3.6%	57.64	59.81	-23.6%	67.22	87.96
8	-61.4%	27.50	71.22	-42.2%	57.94	100.21	-49.7%	67.36	133.82

4.2 Performances of the proposed control scheme with different speed limits

With the verified control scheme, the performance of trajectory planning is tested with different traffic scales and speed limits. The traffic scalers 2, 4, 6 and 8 are chosen for the investigation of the performances of the proposed control strategies at different speeds with the same communication range, which is 400 m. The selected speed limits range from 15 m/s (54 km/h) to 35 m/s (126 km/h) with an interval of 5. This research did not test 10 m/s as it is unlikely to exist in the real world in the signalised intersection environment. The results are plotted in *Figure 3*. The detailed results are presented in *Tables A1-A4* in the Appendix section. For traffic delay, it can be observed that reduction is the greatest when the speed limit is 15 m/s and 20 m/s at a traffic scaler of 8. The reduction trend is similar among the speed limits of 25 m/s (90 km/h), 30 m/s (108 km/h) and 35 m/s. This is consistent with expectations since the maximum speed is higher and the capacity of the road increases in the base scenario as well. When the road capacity increases in the base scenario, the vehicles do not have to experience significant traffic delays on the traffic scaler of 8. While for the speed limit of 15 m/s, the road capacity is even less compared to the 20 m/s. Therefore, the results show that the proposed control scheme brings more benefits when the speed limit is 15 m/s compared to the speed limit of 20 m/s.

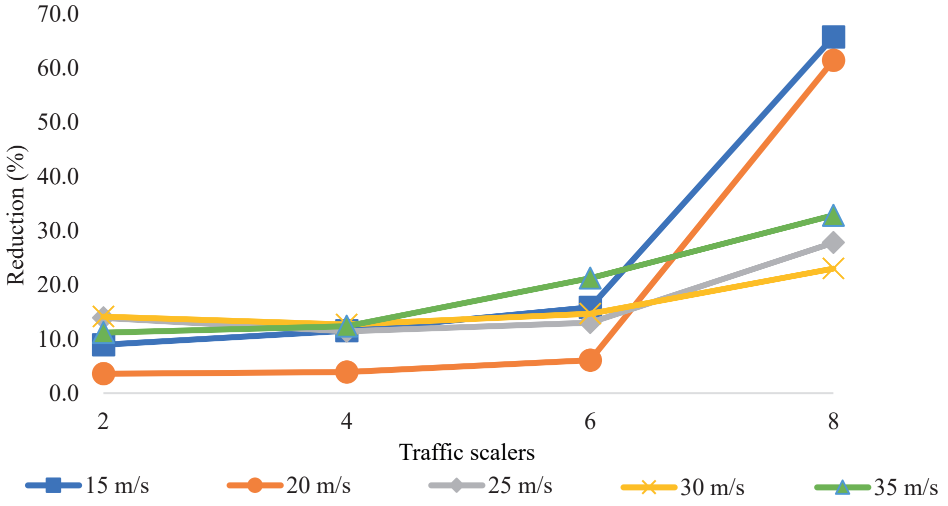


Figure 3 – Traffic delay reduction in percentage

Figure 4 presents the fuel consumption results for different speed limits. The average fuel consumption reduction percentage shows a more regularised pattern at a traffic scaler of 8. The pattern is that the speed limit is higher and the average fuel consumption reduction percentage is lower. When the speed limit is higher, the vehicles are allowed to travel through the intersection at higher speeds within a shorter time, which naturally burns more fuel. In addition, the relatively high fuel consumption in the base scenario also causes the improvement magnitudes in percentage to be smaller compared to lower speed limit scenarios. *Figure 4* presents the travel time reduction in percentage. The travel time reduction percentage across different speed limits shows a similar pattern as in *Figure 5*. Since the traffic delay is derived from actual travel time and ideal travel time (constant if the maximum speed and distance are fixed), this result is reasonable and can provide support for the traffic delay results.

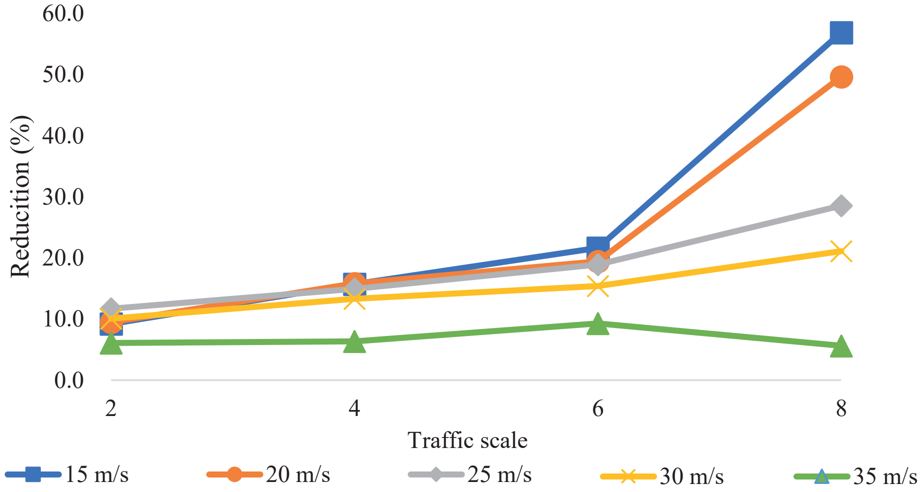


Figure 4 – Fuel consumption reduction in percentage

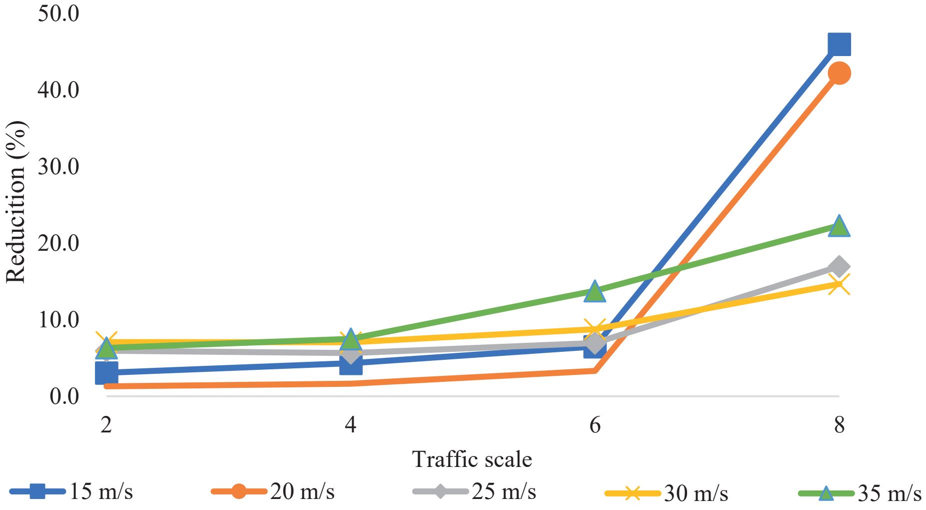


Figure 5 — Travel time reduction in percentage

4.3 Performances with different distances toward the intersection

It is also worth exploring the performances of the proposed control strategy with different distances toward the intersection. Employing the same settings in section 5.1, this research further tested communication ranges of 200 m, 300 m, 500 m and 600 m. Based on [18, 19], the average communication range between vehicles and the intersection is 300 metres. The results show that the proposed control strategies can maintain stable performances in different communication ranges in terms of traffic delay, fuel consumption and travel time. However, no clear pattern can be observed for the improvement magnitudes across different distances in light and medium traffic volume scenarios, which may be attributed to the compounding effects of vehicle random insertion into the road network (random initial speeds and random depart speeds). At the traffic scaler of 8, vehicles without the proposed control strategy are oversaturated in all scenarios and thus produce high traffic delay, fuel consumption and travel time. Overall, the improvement magnitudes increase along with the communication range increasing in terms of traffic delay, fuel consumption and travel time. This is potentially because longer distances allow for more freedom for trajectory planning. Since traffic delay, fuel consumption and travel time all show a similar pattern and to avoid redundancy, the traffic delay graph is presented in *Figure 6*. The detailed results are presented in *Tables A5-A8* in the Appendix section.

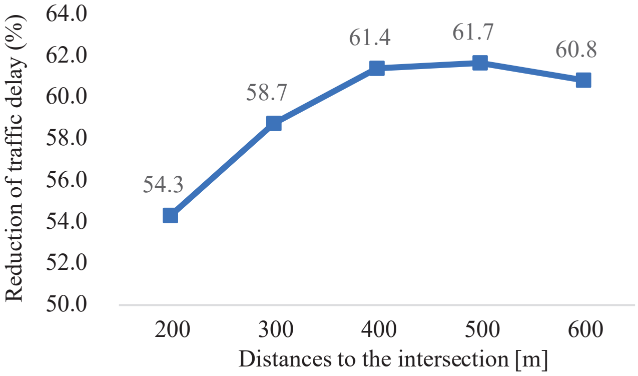


Figure 6 – Traffic delay reduction across different distances at the traffic scaler of 8

5. CONCLUSIONS

This research proposed a combined control strategy for CAVs in a fixed signal intersection environment. The applied trajectory planning is a revision from the existing literature which requires the inputs of arrival time and final speed. Deriving from the trajectory planning methods based on existing work, this research examined the maximum possible final speed that allows for the existence of a solution while ensuring the improvement of capacity. As for the arrival time of CAVs, a reservation-based control framework was proposed to assign the arrival time of CAVs in the fixed signal-controlled intersection. Based on the arrival time allocation control framework, a virtual platoon control was also established which groups the vehicles into a platoon to reduce the computation burden. Vehicles inside the platoon run on the road based on the default car-following model. The platoon leaders' trajectories were planned according to the proposed control strategies. These proposed control strategies for CAVs passing the fixed signalised intersection have been successfully tested in various scenarios including traffic demand scenarios, speed limits and distances. In the base scenario, IDM was selected as the car-following logic with the default car-following parameters.

The results show that the proposed control strategies can maintain fair performance until the traffic scaler is up to 8 (800 veh/h/lane). The proposed control strategy can reduce traffic delay, fuel consumption and travel time simultaneously in all designed traffic scales. This control strategy works best when the intersection is near capacity, in this research, i.e. 800 veh/h/lane.

For the different speed limit scenarios, when the speed limit is lower, the road capacity is lower, and the improvement magnitudes brought by the proposed control strategies are more significant. Therefore, the improvement magnitude is larger in the designed scenario of 15 m/s, 20 m/s in this research. As for the different distances, the proposed control strategies have stable performances in different communication range scenarios. At the demand of near-to-capacity scenarios, the improvement magnitudes increase when the distances increase overall.

Current research considered a simplified isolated intersection, future research may modify the control strategies to suit the multiple intersection environment, in which the green window within two signalised intersections is identified and trajectory planning is implemented based on such green window. Furthermore, platooning control can be employed for the vehicles inside the virtual platoon defined in this research, which could potentially increase the robustness of the proposed control strategy and intersection capacity.

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在固定信号控制的交叉口中，带有轨迹规划的互联和自动驾驶车辆的表现评估

互联和自动驾驶车辆（CAVs）被公认为交通工程领域的技术趋势。作为CAVs最受欢迎的功能之一，轨迹规划引起了学术界和工业界的广泛关注和兴趣。分段式轨迹规划因其在计算和部署方面的简易性和稳健性而越来越受欢迎。通过探索分段式轨迹在不同CAVs和交叉口设置下的影响，可以提供建设性的建议和指导。本研究提出了一种用于固定信号时序环境下分段式轨迹规划的控制策略。为了测试该控制策略的效果，本研究设计了简化的固定信号交叉口场景，并实现了CAVs在不同交通需求、距离和速度限制下的分段式轨迹规划功能。结果表明，所提出的控制策略在不同交通场景中表现出稳定的优越性，尤其在交通流量接近最大道路承载力时表现出色。

关键词：
互联和自动驾驶车辆，轨迹优化，固定信号控制交叉口，虚拟车队

APPENDIX

Table A1 – Performances of the proposed control in speed limit of 15 m/s

Scaler	Traffic delay [s]			Fuel consumption [ml]			Travel time [s]		
	Reduction	**OP**	**Base**	**Reduction**	**OP**	**Base**	**Reduction**	**OP**	**Base**
2	9%	19.26	21.15	9%	61.74	68.00	3%	59.84	61.74
4	12%	21.44	24.23	16%	59.47	70.55	4%	62.02	64.81
6	16%	23.68	28.13	22%	57.08	72.86	6%	64.26	68.71
8	66%	32.42	94.55	57%	64.78	150.32	46%	72.99	135.13

Table A2 – Performances of the proposed control in speed limit of 25 m/sm/s

Scaler	Traffic delay [s]			Fuel consumption [ml]			Travel time [s]		
	Reduction	**OP**	**Base**	**Reduction**	**OP**	**Base**	**Reduction**	**OP**	**Base**
2	14%	15.81	18.36	12%	72.76	82.40	6%	40.18	42.72
4	11%	21.20	23.92	15%	78.10	91.84	6%	45.56	48.28
6	13%	24.59	28.25	19%	78.97	97.39	7%	48.95	52.61
8	28%	27.66	38.29	29%	78.20	109.47	17%	52.03	62.65

Table A3 – Performances of the proposed control in speed limit of 30 m/s

Scaler	Traffic delay [s]			Fuel consumption [ml]			Travel time [s]		
	Reduction	**OP**	**Base**	**Reduction**	**OP**	**Base**	**Reduction**	**OP**	**Base**
2	14%	17.77	20.69	10%	84.83	94.33	7%	38.08	40.99
4	13%	22.34	25.58	13%	91.82	105.91	7%	42.65	45.89
6	15%	25.97	30.42	15%	93.44	110.49	9%	46.27	50.72
8	23%	27.61	35.84	21%	92.43	117.17	15%	47.92	56.15

Table A4 – Performances of the proposed control in speed limit of 35 m/s

Scaler	Traffic delay [s]			Fuel consumption [ml]			Travel time [s]		
	Reduction	**OP**	**Base**	**Reduction**	**OP**	**Base**	**Reduction**	**OP**	**Base**
2	11%	20.12	22.64	6%	98.22	104.61	6%	37.53	40.06
4	12%	23.79	27.13	6%	107.46	114.75	7%	41.20	44.54
6	21%	25.38	32.21	9%	108.83	119.97	14%	42.79	49.62
8	33%	24.82	36.94	6%	118.37	125.43	22%	42.23	54.35

Table A5 – Performances of the proposed control with a communication range of 200 m

Scaler	Traffic delay [s]			Fuel consumption [ml]			Travel time [s]		
	Reduction	**OP**	**Base**	**Reduction**	**OP**	**Base**	**Reduction**	**OP**	**Base**
2	9%	19.38	21.29	10%	57.94	64.65	5%	39.78	41.69
4	11%	21.02	23.73	14%	58.61	68.19	6%	41.43	44.12
6	14%	23.40	27.14	17%	59.26	71.43	8%	43.80	47.54
8	54%	23.74	51.95	40%	60.05	99.87	39%	44.14	72.35

Table A6 – Performances of the proposed control with a communication range of 300 m

Scaler	Traffic delay [s]			Fuel consumption [ml]			Travel time [s]		
	Reduction	OP	Base	Reduction	OP	Base	Reduction	OP	Base
2	12%	15.90	18.04	11%	59.31	66.67	5%	41.37	43.51
4	12%	19.08	21.78	16%	61.04	72.68	6%	44.55	47.24
6	11%	24.07	26.99	19%	63.15	78.26	6%	49.53	52.46
8	59%	27.34	66.27	48%	63.65	122.13	42%	52.80	91.73

Table A7 – Performances of the proposed control with a communication range of 500 m

Scaler	Traffic delay [s]			Fuel consumption [ml]			Travel time [s]		
	Reduction	OP	Base	Reduction	OP	Base	Reduction	OP	Base
2	2%	20.34	20.67	9%	71.84	79.28	1%	55.90	56.22
4	8%	22.23	24.16	16%	70.58	84.11	3%	57.78	59.71
6	11%	24.19	27.06	21%	68.13	86.16	5%	59.74	62.61
8	62%	28.57	74.51	51%	70.56	143.91	42%	64.12	110.06

Table A8 – Performances of the proposed control with a communication range of 600 m

Scaler	Traffic delay [s]			Fuel consumption [ml]			Travel time [s]		
	Reduction	OP	Base	Reduction	OP	Base	Reduction	OP	Base
2	13%	17.41	19.92	11%	74.50	84.10	4%	57.67	60.17
4	14%	19.71	22.87	15%	73.85	87.28	5%	59.97	63.12
6	16%	23.22	27.50	21%	71.91	90.69	6%	63.48	67.75
8	61%	27.06	69.06	49%	72.22	142.03	38%	67.32	109.32