Frontiers in Traffic and Transportation Engineering (2023)
Clausius Scientific Press, Canada

DOI: 10.23977/ftte.2023.030103
ISSN 2616-2334 Vol. 3 Num. 1

Speed Optimization for Single Connected Vehicle at Congested Signalized Intersection Using C-V2X

Xiaoyuan Yue*, Rui Liang, Weiyi Qin

SAIC Volkswagen Automotive Co., Ltd, 63. Luopu Road, Shanghai, China
yuexiaoyuan@csvw.com
**Corresponding author*

Keywords: Signalized Intersection, Congested Traffic, Speed Optimization, Energy Consumption, C-V2X

Abstract: With the continuous development and popularity of the automobile industry, people's demand for mobility has gradually increased, which in turn has caused traffic congestion and risen energy consumption. In this paper, based on the C-V2X technology, combined with traffic flow simulation model IDM and fuel consumption evaluation model VT-Micro, the speed advisory algorithm is optimized to improve the problem of high collision risk between the single connected vehicle and queuing vehicles when the single connected vehicle drives to the congested signalized intersection. The simulation results indicate that the stability of the vehicle's driving status can improve the fuel economy. The speed optimization algorithm proposed in this paper can effectively avoid the risk of vehicle collision and significantly reduce fuel consumption by approximately 47% when facing congested signalized intersections.

1. Introduction

The rapid development of the automotive industry has increased the efficiency of people's mobility, but at the same time it has led to problems such as traffic congestion and rising energy consumption. In signal-controlled areas of the urban road traffic network, vehicles will frequently speed up, slow down and keep idling. Frequent switching between the three modes worsen fuel economy and cause more air pollution in the signalized intersections [1-2]. Fortunately, with the emergence and development of C-V2X (Cellular-Vehicle to Everything) technology, the above issue is being overcame gradually.

C-V2X is a wireless communication technology for automobile based on cellular communication technology [3-4]. It can realize the communication between vehicle and vehicle (V2V), vehicle and pedestrian (V2P), vehicle and infrastructure (V2I), vehicle and network (V2N), making it easy to share information with each other. In the signalized intersections, the V2I technology enables CVs(Connected Vehicles) which equipped with OBU (On Board Unit) to obtain real-time traffic control information and map information from RSU(Road Side Unit) which allows CVs to estimate the time to reach the stop line, the status of the signal lights at that time and give a reasonable advisory speed range for the driver so that the vehicle can pass the signalized intersection economically and reduce passenger discomfort from frequent acceleration and deceleration.

Some studies have shown that the vehicle can reduce the energy consumption when the driver obtains the intersection signal information and adopts the corresponding reasonable driving strategy before the vehicle passes the intersection [5-8]. Liu X G et al. constructed a fuel consumption emission model based on the association between target speeds and established an eco-driving speed control strategy. The experimental results demonstrated that the strategy could reduce fuel consumption by 6.6% in the case of low road saturation [9]. With the help of intersection vehicle-road cooperative communication system, Meng Z aims to find the most efficient speed guidance trajectory by minimizing fuel consumption per unit distance. The proposed speed guidance strategy was simulated using MATLAB, and the results indicated a reduction in fuel consumption of over 10% [10]. Based on the dynamic time-space relationship between bus operation, signalized intersections, and bus stops, Wang X et al. developed a regional judgment model to assess bus arrival punctuality. They also designed an optimal control method using multi-objective optimization for interval speed. Simulation results showed that the proposed method can reduce bus fuel consumption by an average of 7.32 mL [11].

Most studies on speed optimization of CVs primarily focus on the technical aspects of intersection signal information. However, the real traffic environment is highly complex and there are other factors which worth further exploration and research to dig in.

2. Problem Description

Due to the limitations of broadcast messages from RSU, the traditional speed optimization algorithm can only utilize vehicle's own location and status information, along with static map information such as lane turns, speed limits, as well as the signal phase and countdown information of the traffic light ahead. These inputs are used to calculate advisory speed for CVs.

In addition to traffic lights, there are various other factors that can significantly affect vehicle speed in a real traffic environment. One factor that frequently occurs at signalized intersections is vehicle queuing or traffic congestion. As shown in Figure 1, if a CV strictly follows the advisory speed provided by the traditional speed optimization algorithm, it may encounter a significant risk of collision with queuing vehicles at congested intersections.

a) Smooth Urban Road

b) Traffic Congestion

Figure 1: Performance of the traditional speed optimization algorithm in different situations

The advancement of roadside sensing devices and the broadening of C-V2X direct communication message sets have enabled Road Side Units (RSUs) to provide CVs with a greater amount of information to aid in their decision-making process regarding driving behaviour. When a CV approaches a signalized intersection, the CV establishes a connection with RSU via C-V2X communication technology. Through this connection, the CV receives traffic lights time assignment and real-time status from the traffic lights controller. Additionally, RSU sends map information and vehicle queuing situations in each lane collected by the roadside sensing device such as Radar and

Camera to CV. The speed optimization algorithm initially ascertains the vehicle's position and driving direction within the road network by utilizing the vehicle's own positioning, driving status and static map information. Subsequently, it extracts the traffic lights and vehicle queuing information that lie ahead of the vehicle's driving direction from the data transmitted by the RSU. Ultimately, it integrates the aforementioned types of information to calculate a suitable speed range and display it to the driver through the cockpit display terminal. Traffic environment and data transfer flow in this paper are shown in Figure 2, 3.

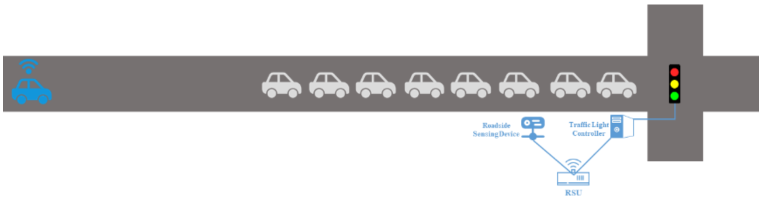

Figure 2: Traffic environment based on V2I

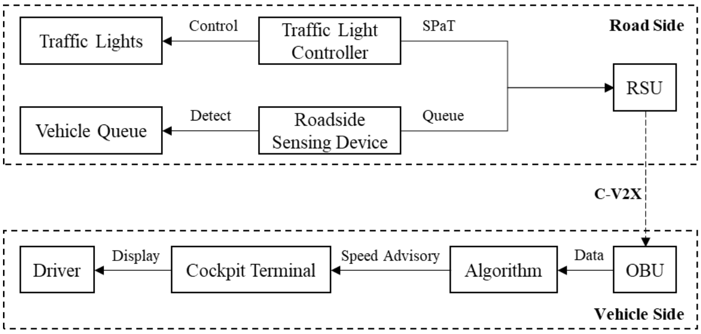

Figure 3: Data transfer flow

In this paper, a novel speed optimization algorithm is presented for the signalized intersection handling congestion conditions. The goal of our algorithm is to reach a recommended speed to pass the intersection while guaranteeing safety and efficiency. In our design, we utilize a fuel consumption model to evaluate the economy of the algorithm

3. Model Construction

3.1 Assumption and Parameter

Table 1: Parameters

Variable symbol	Parameter meaning
$s(t), v(t), a(t)$	The instantaneous position, speed and acceleration of CV on the road at time t
t_{in}	The moment when CV drives into the RSU coverage area
t_{out}	The moment when the CV leaves the signalized intersection
t_{step}	Time step in the process of updating vehicle driving status
$1,2,\ldots,n-1,n$	Reference number of all vehicles on the road
a_{ac}, a_{de}	Maximum acceleration and maximum deceleration values
$MOE(t)$	The instantaneous fuel consumption
L	The length of the path from one intersection to another
l	The vehicle length
t_R, t_G	Full duration of red and green lights
t_r, t_g	Remaining duration of red and green lights

The performance of speed optimization algorithm in this paper is subject to the following premise assumptions as below:

- Disregarding C-V2X data transmission delay and driver's reaction time
- Disregarding the secondary queuing situation, that is, all queuing vehicles can be dissipated in one green light period;
- Disregarding the situation of CV cannot pass the intersection within two signal cycles;
- The road speed limit needs to be considered.

The specific parameters involved in the speed optimization algorithm are shown in Table 1.

3.2 Vehicle Model

Vehicle models are the basis for road traffic simulation. Since this paper studies the speed optimization and energy consumption of a single connected vehicle affected by congested traffic flow in the signalized intersection, the vehicle models mainly involve the Car Following (CF) model used to simulate congested traffic flow and the energy consumption model for evaluating the effect of speed optimization besides the basic kinematical equations.

3.2.1 Intelligent Driver Model (IDM)

CF behaviour is one of the basic microscopic driving behaviours, which describes the interaction between two neighbouring vehicles on a single-lane way where overtaking is restricted. From the perspective of traffic engineering, the types of CF model can be categorized into stimulus-response, safety-distance, psycho-physiological and artificial intelligence. IDM belongs to the time-continuous and safe-distance type of CF model with many advantages such as the moderate number of parameters, defining mechanical meaning, well empirical conformity, and the ability to describe the different states from the free flow to the fully congested flow with a unified model. IDM has been widely used in the simulation of traffic flow. The formula for IDM to calculate safe acceleration is as follows:

$$a_n(t) = a_{ac} \times \left(1 - \left(\frac{v_n(t)}{v_0}\right)^{\delta} - \left(\frac{s_n^*(t)}{s_n(t)}\right)^2\right) \tag{1}$$

$$s_n^*(t) = s^C + \max\left(0, v_n(t)\tau^C + \frac{v_n(t)\Delta v_n(t)}{2\sqrt{a_{ac} \times a_{de}}}\right) \tag{2}$$

$$\Delta v_n(t) = v_{n-1}(t) - v_n(t) \tag{3}$$

In the above formula, n represents the number of the host vehicle and $n-1$ is the previous vehicle; v_0 represents the maximum speed of the host vehicle travelling in the free traffic flow; δ is the acceleration index; $s_n^*(t)$ represents the expected CF distance between neighbouring vehicles; s^C, τ^C are the minimum value of safe distance and headway, respectively.

Based on the above IDM, host vehicle driving status updates are described separately according to the presence or absence of a previous vehicle. For the case where there is no vehicle ahead, the host vehicle expects to travel at maximum speed, i.e., $a_n(t) = a_{ac}$. According to the time interval ($\mathrm{t_{step}}$) of the update, the speed needs to be changed at time $t + t_{step}$ to: $v_n(t + t_{step}) = \min\{v_{limit}, v_n(t) + a_n(t)t_{step}\}$. Update the acceleration at time t to: $a_n(t) = \frac{v_n(t+1) - v_n(t)}{\mathrm{t_{step}}}$. Update the position at time $t + t_{step}$ to: $s_n(t + t_{step}) = s_n(t) + v_n(t)t_{step} + \frac{1}{2}a_n(t)t_{step}^2$.

For the case where there is a vehicle ahead, the process of updating the motion state of the host vehicle consists of the following steps:

(1) Calculate the relative distance:

$$\Delta s_n(t) = s_{n-1}(t) - s_n(t) - l \tag{4}$$

(2) Calculate the relative speed:

$$\Delta v_n(t) = v_{n-1}(t) - v_n(t) \tag{5}$$

(3) Calculate the desired CF distance:

$$s_n^*(t) = s^C + \max(0, v_n(t)\tau^C + \frac{v_n(t)\Delta v_n(t)}{2\sqrt{a_{ac} \times a_{de}}}) \tag{6}$$

(4) Calculate the acceleration:

$$a_n(t) = a_{ac} \times (1 - \left(\frac{v_n(t)}{v_0}\right)^{\delta} - \left(\frac{s_n^*(t)}{s_n(t)}\right)^2) \tag{7}$$

(5) Update the speed:

$$v_n(t + t_{step}) = \max\{0, v_n(t) + a_n(t)t_{step}\} \tag{8}$$

$$v_n(t + t_{step}) = \min\{v_{limit}, v_n(t + t_{step})\} \tag{9}$$

(6) Update the acceleration:

$$a_n(t) = \frac{v_n(t+1) - v_n(t)}{\mathrm{t_{step}}} \tag{10}$$

(7) Update the position:

$$s_n(t + t_{step}) = s_n(t) + v_n(t)t_{step} + \frac{1}{2}a_n(t)t_{step}^2 \tag{11}$$

3.2.2 Virginia Tech Microscopic(VT-Micro) Model

Automotive micro-driving fuel consumption models can be roughly categorized into three types based on different inputs: power, engine characteristic parameters, and vehicle driving status. In this paper, based on the above traffic flow simulation model IDM, it is easy to obtain the speed and acceleration information of the vehicle, but the engine state parameters are not accessible to the model. Considering the demand of the output accuracy as high as possible, this paper selects the fuel consumption model whose input is the vehicle driving status. Among them, the VT-Micro model based on velocity-acceleration regression is the most typical model.

The VT-Micro model is developed by researchers at Virginia Tech by utilizing statistical theory to classify more than 60 test vehicles into 7 categories, obtaining real data of different types of vehicles through experiments, and developing the model through multiple linear regression methods, with the following expressions:

$$\ln MOE(t) = \begin{cases} \sum_{i=0}^{3}\sum_{j=0}^{3} M_{ij} \times v(t)^i \times a(t)^j, a \geq 0 \\ \sum_{i=0}^{3}\sum_{j=0}^{3} L_{ij} \times v(t)^i \times a(t)^j, a < 0 \end{cases} \tag{12}$$

In the above formula, M_{ij}, L_{ij} represents the regression coefficient at acceleration and deceleration, respectively.

Selection of appropriate regression coefficients for calculating the instantaneous fuel consumption of the vehicle allows the model to be applied to the speed interval [0, 120] km/h and the acceleration interval [-16, 16] km/h/s, which is applicable to the study of this paper.

3.3 Speed Optimization Algorithm at Signalized Intersections

When a CV enters the road covered by C-V2X, it can be categorized into two types of vehicles: one is that there is no other vehicle driving ahead or the vehicle can drive at free flow speed. In this case, the driving behaviour of the vehicle is only affected by the traffic light ahead; the second is that there are other vehicles queuing or in a congested state at the signalized intersection ahead. In this case, the driving behaviour of the vehicle is not only affected by the traffic light ahead, but also by the driving status of the vehicles queuing ahead.

3.3.1 In Case of Free Flow

The driving behaviour of the host vehicle is affected by the signal phase and time remaining of the traffic lights ahead. So there are two situations when the host vehicle approaches an intersection: one is coming to a green light; the other one is coming to a red light. The purpose of speed optimization is to enable the host vehicle to pass the signalized intersection as quickly and smoothly as possible.

For situation one, the formula for calculating the minimum arrival speed v_f within this signal cycle is as follow:

$$v_f = \frac{L-s(t)}{t_g} \tag{13}$$

If $v_f \le v_{limit}$, the advisory speed range is $[v_f, v_{limit}]$;

If $v_f > v_{limit}$, the host vehicle cannot pass through the intersection within the remaining green light time. Then need to plan to pass at next green light time. The formula for calculating the minimum arrival speed v_{f_min} and the maximum arrival speed v_{f_max} are as follows:

$$v_{f\_min} = \frac{L-s(t)}{t_g+t_R+t_G} \tag{14}$$

$$v_{f\_max} = \frac{L-s(t)}{t_g+t_R} \tag{15}$$

The advisory speed range is $[v_{f\_min}, \min\{v_{f\_max}, v_{limit}\}]$.

For situation two, the formula for calculating the minimum arrival speed v_{f_min} and the maximum arrival speed v_{f_max} are as follows:

$$v_{f\_min} = \frac{L-s(t)}{t_r+t_G} \tag{16}$$

$$v_{f\_max} = \frac{L-s(t)}{t_r} \tag{17}$$

If $v_{f\_min} \le v_{limit}$, the advisory speed range is $[v_{f\_min}, \min\{v_{f\_max}, v_{limit}\}]$;

If $v_{f\_min} > v_{limit}$, the host vehicle cannot pass through the intersection within the remaining green light time. Then need to plan to pass at next green light time. The formula for calculating the minimum arrival speed v_{f_min} and the maximum arrival speed v_{f_max} are as follows:

$$v_{f\_min} = \frac{L-s(t)}{t_r+t_R+2t_G} \tag{18}$$

$$v_{f\_max} = \frac{L-s(t)}{t_r+t_R+t_G} \tag{19}$$

The advisory speed range is $[v_{f\_min}, \min\{v_{f\_max}, v_{limit}\}]$.

3.3.2 In Case of Vehicle Queuing

When the intersection is in a congested state, the speed optimization of the host vehicle should also consider the queue dissipation time (t_d), otherwise it is easy to collide with the tail vehicle in the queue. Similarly, calculate the advisory speed range based on the hitting light colour.

For host vehicle hitting the green light, the formula for calculating the minimum arrival speed v_{f_min} and the maximum arrival speed v_{f_max} are as follows:

$$v_{f\_min} = \frac{L-s(t)}{t_g} \tag{20}$$

$$v_{f\_max} = \frac{L-s(t)}{t_d} \tag{21}$$

If $v_{f\_min} \leq v_{limit}$, the advisory speed range is $[v_{f\_min}, \min\{v_{f\_max}, v_{limit}\}]$;

If $v_{f\_min} > v_{limit}$, the host vehicle cannot pass through the intersection within the remaining green light time in this signal cycle. The advisory speed range calculation is the same as formulas 14 and 15.

For host vehicle hitting the red light, the formula for calculating the minimum arrival speed v_{f_min} and the maximum arrival speed v_{f_max} are as follows:

$$v_{f\_min} = \frac{L-s(t)}{t_r+t_G} \tag{22}$$

$$v_{f\_max} = \frac{L-s(t)}{t_r+t_d} \tag{23}$$

If $v_{f\_min} \leq v_{limit}$, the advisory speed range is $[v_{f\_min}, \min\{v_{f\_max}, v_{limit}\}]$;

If $v_{f\_min} > v_{limit}$, the host vehicle cannot pass through the intersection within the remaining green light time in this signal cycle. The advisory speed range calculation is the same as formulas 18 and 19.

4. Empirical Study

4.1 Parameter Value

Table 2 lists the relevant parameters for simulating the traffic environment.

Table 3, 4 list the key parameters of the model IDM and VT-Micro.

Table 2: Traffic environment

Variable symbol	Value	Unit
L	200	m
t_G	20	s
t_R	20	s
v_{limit}	60	km/h

Table 3: IDM parameters

Variable symbol	Value	Unit
a_{ac}	4	m/s^2
a_{de}	4	m/s^2
s^C	5	m
τ^C	0.8	s
δ	4	-

Table 4: VT-Micro parameters

Coefficient	v^0	v^1	v^2	v^3
$a \geq 0$				
a^0	-7.735	0.02799	-2.228E-4	1.09E-6
a^1	0.2295	0.0068	4.402E-5	4.8E-8
a^2	-5.61E-3	-7.722E-4	7.9E-7	3.27E-8
a^3	9.773E-5	8.38E-6	8.17E-7	-7.79E-9
$a < 0$				
a^0	-7.735	0.02804	-2.199E-4	1.08E-6
a^1	-0.01799	7.72E-3	-5.219E-5	2.47E-7
a^2	-4.27E-3	8.375E-4	-7.44E-6	4.87E-8
a^3	1.8829E-4	3.387E-5	2.77E-7	3.79E-10

4.2 Simulation Results and Analysis

4.2.1 In Case of Free Flow

The simulation results when the road is in free flow status are shown in Figure 4. It shows position of all vehicles and the cumulative fuel consumption of the host vehicle over time. Among them, V1 represents other vehicle on the road; HV0 represents the host vehicle driven according to IDM; HV1 represents the host vehicle driven at a speed recommended by the traditional speed advisory algorithm; HV2 represents the host vehicle driven at the advisory speed according to the optimized speed advisory algorithm in this paper.

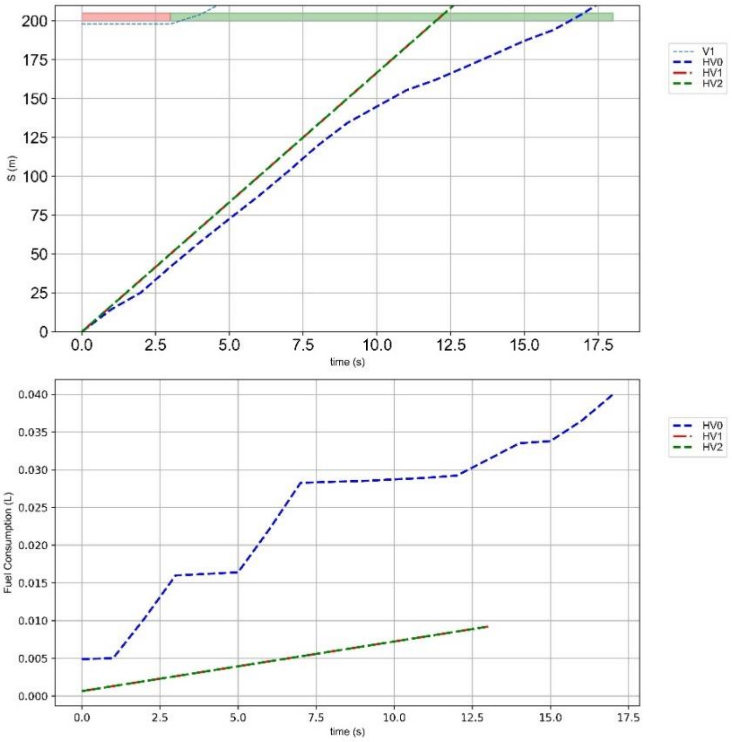

Figure 4: Spatial-temporal trajectory and Cumulative fuel consumption

From Figure 4, it can be seen that:

(1) HV0 adopts acceleration and deceleration behaviour according to IDM throughout the entire

driving process and the travel time is longer than HV1, HV2;

(2) HV1 and HV2 adopt the same driving behaviour of driving at maximum speed or limited speed. In this case, the advisory speed output by both speed optimization algorithms are the same;

(3) The host vehicle driving at the speed recommended by the vehicle model and speed optimization algorithm can reduce fuel consumption by approximately 77% (HV0:0.0399 L; HV1&HV2:0.0092 L).

Figure 5 shows the instantaneous fuel consumption of the host vehicle during driving. It can be observed that the acceleration and deceleration behaviours of the vehicle will bring about a significant amount of fuel consumption. Therefore, the stability of the vehicle's driving status can improve the fuel economy of the vehicle.

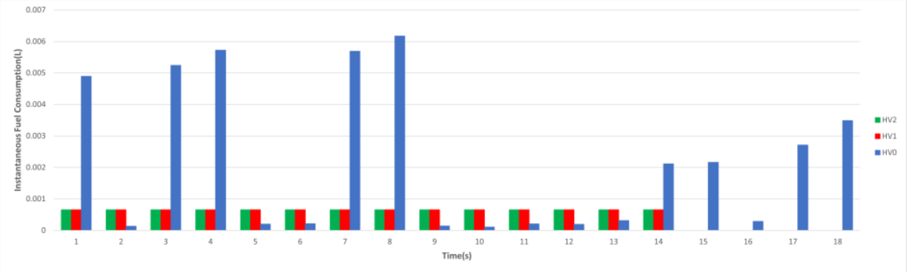

Figure 5: Instantaneous fuel consumption

4.2.2 In Case of Vehicle Queuing

The simulation results when the intersection is in a congested status are shown in Figure 6. It shows position of all vehicles and the cumulative fuel consumption of the host vehicle over time. Among them, V1-V11 represent vehicles queuing at the intersection; HV0, HV1 and HV2 represent the same meaning as the free flow case.

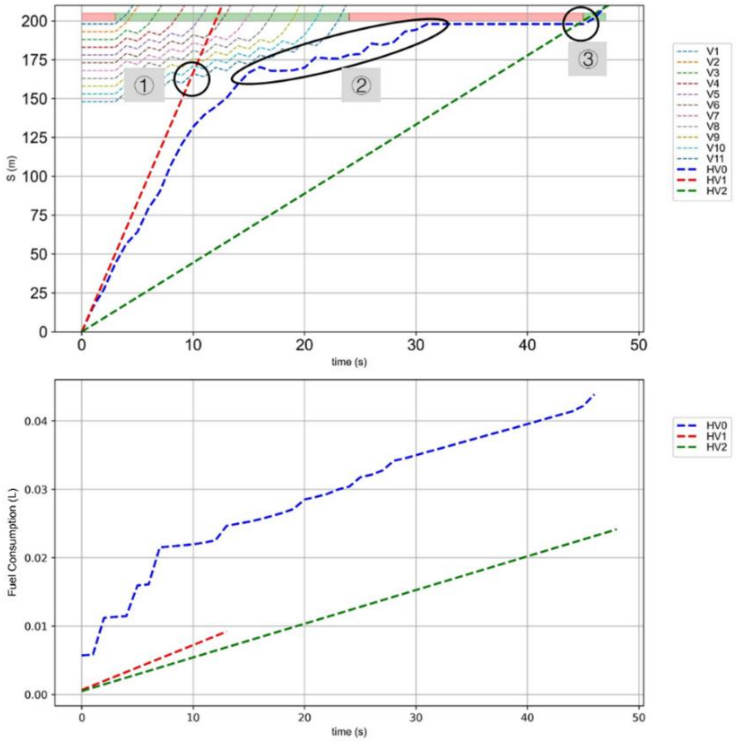

Figure 6: Spatial-temporal trajectory and Cumulative fuel consumption

From Figure 6, it can be seen that:

(1) HV0 adopts more acceleration and deceleration behaviour throughout the entire driving process(marked②), and stopped at idle for a long time due to encountering red lights at intersections;

(2) HV1 will collide with the tail vehicle of the queue at the position marked① in a congested intersection;

(3) HV2 can drive at a constant speed through the congested intersection(marked③), reducing the time and energy consumption for starting and acceleration compared to HV0;

(4) The host vehicle driving at the speed recommended by the vehicle model and speed optimization algorithm provided in this paper can avoid the risk of vehicle collision and reduce fuel consumption by approximately 47%(HV0:0.0439 L; HV2:0.0232 L).

5. Conclusion

In response to the limitation of the traditional speed optimization algorithm in dealing with traffic congestion at signalized intersections, this paper applies IDM to simulate congested traffic and proposes an algorithm optimization method based on C-V2X technology. The simulation results in the free flow situation show that the acceleration and deceleration process of the vehicle will bring more fuel consumption. Speed optimization algorithm can reduce the frequency of acceleration and deceleration, improve the fuel economy on the basis of ensuring the vehicle driving safety. When facing traffic congestion at intersection, the optimized speed advisory algorithm proposed in this paper can effectively solve the problem of vehicle conflicts in traditional speed advisory algorithm. In addition, taking the traffic scenario constructed in this paper as an example, it can reduce fuel consumption by 47%, which has a significant effect on improving fuel economy. As mentioned in this paper, the real traffic environment is highly complex. In the future, we will further include other factors that affect the driving speed of vehicles in the section, such as lane change, pedestrian crossing, etc.

References

[1] Jacek O, Konrad B. (2022) Estimation of Vehicle Energy Consumption at Intersections Using Microscopic Traffic Models. Energies, 16(1).

[2] Liu X L, Hu J, Hu X Y, et al. (2020) Influencing Factors and Countermeasures of Vehicle Energy Consumption at Signalized Intersections of Urban Roads. Transportation Enterprise Management, 35(01):76-78

[3] Duan X, Jiang H, Tian D, et al. (2021)V2I Based Environment Perception for Autonomous Vehicles at Intersections. China Communications, 18(07):1-12.

[4] Liu P, Jiang P, Shu H, et al. (2022) A New Method for Vehicle Speed Planning and Model Prediction Control under V2I. Journal of Chongqing Jiaotong University (Natural Science), 41(07):27-33.

[5] Xu B, Chen X, Li K, et al. (2019) Double-layer speed optimization for reducing fuel consumption with vehicle-to-infrastructure communication. Journal of Intelligent Transportation Systems, 23(5).

[6] Wu L, Ci Y, Wang Y, et al. (2020) Fuel consumption at the oversaturated signalized intersection considering queue effects: A case study in Harbin, China. Energy, 192(C).

[7] Dan S, Kun J. (2021) Research on Eco-driving of Signalized Intersection Fleet in Vehicle-Road Cooperative Environment. IOP Conference Series: Earth and Environmental Science, 638(1).

[8] Simin H, Cedric C D, Evy R, et al. (2023) Energy-Optimal Speed Control for Autonomous Electric Vehicles Up- and Downstream of a Signalized Intersection. World Electric Vehicle Journal, 14(2).

[9] Liu X G, Wang H N, Hong J W, et al. (2021) Speed Control Strategy and Optimization of Signalized Intersection in Network Environment. Journal of Transportation Systems Engineering and Information Technology, 21(02):82-90.

[10] Meng Z. (2018) A Study on Energy-saving Oriented Green Light Optimal Advisory speed for Single Vehicle at Signalized Intersection Using V2I Communication. Wuhan University of Technology.

[11] Wang X, Jiang P Y, Zhang R H. (2020) A Speed Control Method for Transit Operation Based on Multi-objective Optimization. Journal of Transport Information and Safety, 38(03):32-39+66.