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Research Article

Dissipation Characteristics of Vehicle Queue in V2X Environment Based on Improved Car-Following Model

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In recent years, the technology of Internet of Vehicles has developed rapidly, among which vehicle to everything (V2X) technology is provided with a quite important promotion value in the intelligent transportation field. In V2X environment, the driver can receive real-time information of the motion status of adjacent vehicles and the signal duration of the intersection, and take the decision-making action of manipulating the vehicle in advance, which has a certain impact on the evolution process of queue dissipation. This paper studies the improved OV model based on V2X environment and considering the driver's early response time selects the intersection queue dissipation efficiency as the index to analyze the intersection traffic efficiency and studies the impact of different initial headway, maximum speed, and safety distance on the intersection traffic flow. The simulation results show that compared with the traditional OV model and the OV model considering driver's reaction delay, the model proposed in this paper greatly improves the efficiency of traffic flow recovery after green light, so the model proposed in this paper can promote the stability of traffic flow. The linear stability of the proposed model was analyzed by using the linear stability theory to obtain the stability conditions of the improved model. Furthermore, a simulation environment was established to analyze the vehicle queue dissipation at intersections and to simulate the improved V2X car-following model as well as the platoon dissipation state under different traffic parameters. The research results show that vehicle drivers can obtain traffic flow operation status in real-time through V2X equipment and change the operation of the vehicle itself in a targeted manner, which can significantly improve the safety and stability of traffic flow operation, and greatly raise the dissipation efficiency of the platoon. The method proposed in this paper can increase the queue dissipation rate and shorten the recovery time of the traffic system, respectively.

1. Introduction

Affected by such information as the state of traffic lights at intersections and the real-time movement of adjacent vehicles, periodic accumulation and dissipation of vehicle queues will appear on the road. The microscopic car-following behavior plays an important role in the formation and dissipation mechanism of queuing during the process of vehicle queuing at intersections. It is the premise of making precise traffic control [1], providing traffic information service [2], and establishing traffic guidance strategies [3] to distinguish the vehicle queuing state at signalized intersections on the basis of the microscopic car-following behavior, so as to accurately describe the traffic status at signalized intersections. It is of great significance to intelligent traffic management and control. Queuing state estimation methods in the existing researches are mostly based on the traffic flow accumulation curve, traffic wave theory, or queuing theory. Zhang proposes a V2X (Vehicle to Everything) based TSP control strategy for a single intersection. With the support of V2X communication, the bus can send a priority request before entering the intersection and activate real-time signal priority control at the preceding intersection before the bus reaches the intersection. In this TSP strategy, the queuing time was estimated based on the traffic wave theory [4]. Wu et al. established a cellular automata model with the greedy algorithm for the traffic control of intersections in an autonomous vehicle environment, with autonomous vehicle platoon as the optimization object. The findings suggest that, on the premises of ensuring traffic safety, the control strategy of the proposed model significantly reduces average delays and number of stops as well as increasing traffic capacity [5]. In most situations, these methods assume that the traffic flow follows certain statistical rules, for example, the state of traffic flow remains unchanged or changes continuously according to a certain distribution law, which has obvious shortcomings. Specifically, on the one hand, urban road traffic system is complex as well as highly random. Even in a short period of time, the traffic state may change significantly. Therefore, the queuing model based on historical traffic flow statistics is hard to meet the need of practical application. On the other hand, the impact of individual driver's subjective decision-making behavior on the overall queuing status is of vital importance, which is not considered within the related theoretical methods. Considering the lag of drivers' access to information in traditional environment, many scholars have studied the influence of the improved model on the stability of traffic flow after enhancing the car-following model. Although some contributions have been made, the lack of drivers' access to information under traditional conditions has limited drivers' access to road traffic information.

V2X communication mainly includes V2V (vehicle to vehicle), V2I (vehicle to infrastructure), V2P (vehicle to people), and V2N (vehicle to network). Through V2V technology, the mutual communication between vehicles and vehicles forms a powerful shared information network, which can assist drivers to make advance decisions by making full use of the vehicle's movement status, road conditions and other information.

In V2X environment, drivers queuing up during the intergreen interval can use the wireless communication network to obtain the real-time information about the movement of surrounding vehicles and the light status of the intersection ahead, and then manipulate their vehicles in advance. Within a short period of time before the light turns green, drivers can start their vehicles ahead of time by using the stopping distance to realize the preacceleration of vehicles, breaking through the minimum safe distance in the traditional concept. Accordingly, the car-following behavior has substantially changed, further affecting the dissipation process of the platoon.

However, after sorting out the existing literature, it is found that most of the researchers study in terms of the influence of car-following model on traffic flow characteristics, but fail to consider drivers' control of starting wave in V2X environment from the micro perspective. The whole road traffic information will change drivers' reaction flexibility to vehicle manipulation and microscopic car-following behavior, and further affect the process of vehicle queuing accumulation and dissipation.

In this paper, we study the improved OV model based on V2V environment, comparing the OV model considering driver's reaction delay and the traditional OV model. The linear stability theory is used to analyze and solve the neutral stability conditions of the improved model. A simulation environment was established to analyze the dissipation characteristics of the platoon at intersections under the improved V2X car-following model. Firstly, the effects of different reaction advance times on the vehicle operating parameters were simulated, and secondly, the influence of the model parameters on the reaction advance times and vehicle operating data were simulated. The simulation results show that the proposed model can describe the queue dissipation state more reasonably, and the queue dissipation efficiency at intersections is remarkably raised. The chapters are arranged as following:

In Section 1, the research background and existing problems are described to introduce the research content of this paper. Section 2 summarizes the current research status of related work. Section 3 analyzes the research problems in this paper, introduces parameters to characterize the driver's early reaction time, proposes an improved V2X car-following model, and describes the motion state of the car-following under the improved model. Section 4 uses the linear stability theory to analyze and solve the neutral stability conditions of the improved V2X car-following model, and draws the neutral stability curve. Section 5 builds a simulation environment to analyze the dissipation efficiency of the intersection platoon based on the improved V2X car-following model. Section 6 summarizes and looks forward to the content and deficiencies of this paper.

2. Related Work

Recently, with the development of wireless communication and intelli-sensing technologies, fruitful researches have been conducted on the queuing state estimation of intersections, and a series of phased research results have been achieved. Researchers analyzed the influencing factors of queuing dissipation characteristics from different angles. Thereinto, Mondal et al. evaluated the distance traveled by vehicles when the queue dissipates at a signalized intersection under mixed traffic [6]. Zhou et al. studied the influence of bicycles on the headway of vehicles on direct-through lanes in view of mixed motor and non-motor characteristics of urban signalized intersections in China [7]. Liu et al. analyzed the influence of the countdown signal control on the queue dissipation characteristics of direct-through and left-turn lanes in China [8]. Most of these studies analyze the queue dissipation efficiency from the perspective of signal control and do not consider the influence of the driving behavior of road drivers on the queue dissipation efficiency.

Many scholars have studied the impact of traffic flow changes on traffic flow capacity. Yuan et al. proposed a car-following model considering the randomness of expected acceleration to study the relationship between traffic capacity reduction and driver behavior [9]. The results show that the randomness of expected acceleration is an important influencing factor for the decrease of traffic capacity. Chavis et al. used the signal control strategy to avoid the phenomenon of remaining queues caused by bus stop [10]. Sun et al. studied the effect of current limiting measures on the queuing elimination time induced by single-channel engineering accidents [11]. Chen et al. realized the flexibility and timeliness of dynamic filtering coordinated control of arterial traffic roads based on the queue and dissipation model [12]. These aforementioned scholars have expanded the traffic capacity of intersections to a certain extent by studying the effect of traffic flow changes on queue dissipation efficiency, but the analyses are on macroscopic traffic flows and do not address microscopic traffic flows.

The vehicles in the traffic system are controlled by drivers, and it takes a certain amount of time for drivers to make judgments and decisions based on the driving state of the preceding vehicles. In this regard, many scholars have elaborated the car-following model considering the driver's reaction delay. Jin et al. proposed a delay feedback control based on head distance and speed difference to ensure the stability of the model considering the driver's reaction delay [13]. Li et al. studied the general nonlinear stabilization strategy of the car-following model considering the driver's reaction delay [14]. Zhou et al. established a full speed difference model considering the driver's reaction delay and conducted a nonlinear analysis [15]. In [16, 17], researches were carried out concerning the effect of driver's reaction delay time on traffic flow. Most of the above studies were conducted based on the lag of driver access to information under the traditional environment, and although some success was achieved, the lag of driver information under traditional conditions limited the driver's access to road information.

In V2X environment, the communication between the vehicle and outside world forms a powerful shared information network, which makes full use of the such information as the movement of vehicles and road conditions to assist drivers in making decisions in advance, which in turn affect their driving behavior. In order to make the best of these information, many studies have focused on the evaluation of traffic parameters such as vehicle density [18, 19] and average speed [20]. Considering the average speed effect, Kuang et al. proposed an extended multi expected average speed model [21]. Hua Xuedong et al. established an improved Newell model taking V2V technology into account to study the impact of V2V communication technology on traffic operation [22]. Combining with V2V communication technology, Peng et al. proposed a delay feedback control method for the car-following model [23]. Sun et al. proposed an improved car-following model [24] considering the influence of two continuous vehicles in front under the background of V2V communication technology. Wang et al. presented an extended car-following model to analyze the impact of V2V communication technology on microscopic driving behavior of unsignalized intersections [25]. By sorting out the current researches, it is found that most of the researchers consider the effect of the car following model on the characteristics of traffic flow based on the background of V2X communication technology, excluding drivers' control of the starting wave in V2X environment from a microscopic perspective.

3. Improved V2X Car-Following Model considering Driver's Early Reaction Time

3.1. Problems Analysis. After the signalized lights turn red, vehicles line up and accumulate in front of the stop line. In V2V environment, drivers have access to such real-time information as the release status of forward signal lights and the motion status of neighboring vehicles. The driver gets a real-time status of the traffic flow ahead through the V2V device and is given an advance reaction time before the car in front initiate [26]. In this case, the process of vehicle queue dissipation at the intersection is shown as Figure 1.

Illustrated by the example of any two adjacent vehicles in the platoon, the process of queue and dissipation is specifically decomposed as follows:

(1) S1-Initial state. Both vehicles n and $n+1$ are in a stopping condition, and the stopping distance is h_0, as shown in Figure 1 (S1).

(2) S2-Pre-acceleration state of the following car. Δx is the headway between vehicles n and vehicles $n+1$. The driver obtains the status of the intersection signal lights in real time. In a short time before the light turns green, the driver behind predicts the starting intention of the driver in front, and starts the vehicle in advance within t_f time before the front vehicle starts to preaccelerate by using the stopping distance. Before the actual interval between two vehicles reaches the safe headway h_c, the following adjusts its speed in line with the change of the vehicle distance, as shown in Figure 1 (S2).

(3) S3-Driving state of the following vehicle after the preceding one starts. After the following vehicle starts t_f ahead of time, the front one starts. The following vehicle takes the speed achieved after preacceleration as the initial state, and marches in the light of the preceding vehicle's speed, as shown in Figure 1 (S3).

From the above analysis, it can be seen that in V2X environment, the vehicle queue will bring about a kind of "gathering" phenomenon before the green light is on, which forms a tight vehicle queue with a certain initial speed. Compared with the traditional queue dissipation process, the queue dissipation rate is effectively raised.

3.2. Model Building. OV (Optimal Vehicle) model is one of the basic models to describe the dynamic behavior of vehicles, from which a series of optimization models can be extended such as generalized optimal speed (GF) model [27], full speed difference (FVD) model [28], optimal speed difference (OVD) model [29], etc., which are of great value to the analysis of traffic flow microbehavior. The OV model is used in this paper to optimize and build model of the car-following behavior in V2X environment.

In OV model, the acceleration of the n^{th} vehicle is given by

$$\frac{\mathrm{d}^2 x_n(t)}{\mathrm{d}t^2} = \alpha\left[V\left(\Delta x_n(t)\right) - \dot{x}_n(t)\right]. \tag{1}$$

where α is known as the sensitivity of the transportation system, $x_n(t)$ is the position of the n^{th} vehicle at time t, $\dot{x}_n(t)$ is the speed of the n^{th} vehicle at time t, and $\Delta x_n(t) = x_{n+1}(t) - x_n(t)$ represents the headway of the n^{th} vehicle at time t. $V(*)$ is the optimal velocity function.

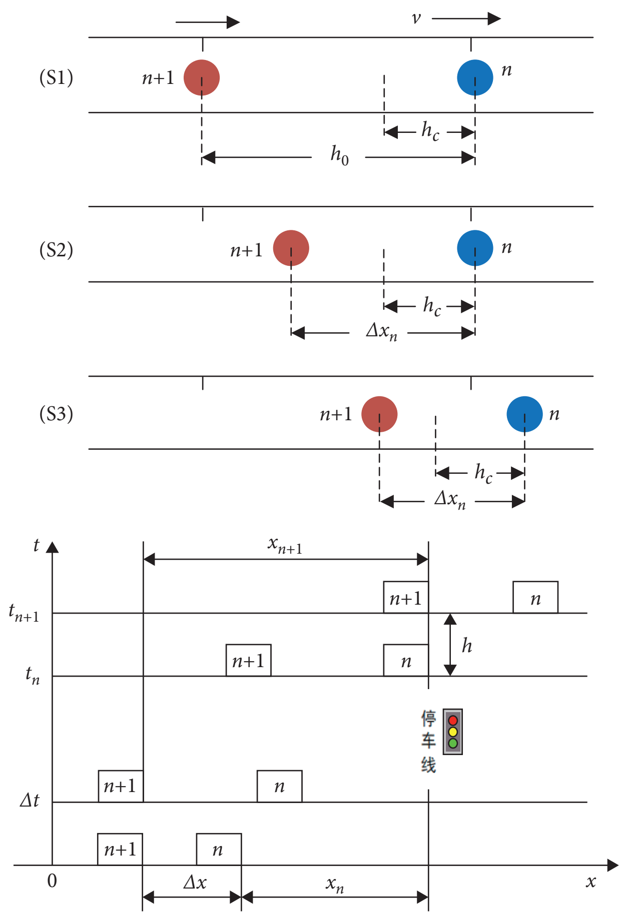


Figure 1: Analysis of car-following behavior in the process of queue dissipation in V2V environment.

Based on the OV model, parameter t_f is introduced to characterize the driver's advance reaction time, and an improved V2X car-following model is proposed. The basic expression is as follows:

$$\frac{d^2 x_n(t)}{dt^2} = \alpha\left[V\left(\Delta x_n\left(t + t_f\right)\right) - \dot{x}_n(t)\right], \tag{2}$$

where t_f presents the driver's advance reaction time. $V(*)$ is the optimal velocity function, adopting practical tanh type optimal velocity function:

$$V(\Delta x_n(t)) = \frac{v_{\max}}{2}\left[\tanh\left(\Delta x_n(t) - h_c\right) + \tanh\left(h_c\right)\right], \tag{3}$$

where h_c is safe headway and $v_{\max}$ presents the maximum speed. $V(\Delta x_n(t))$ also expects the stable speed and is subject to the following conditions:

$$V(\Delta x_n(t)) \geq 0, V(0) = 0, \lim_{\Delta x_n(t) \longrightarrow \infty} V(\Delta x_n(t)) = v_{\max}. \tag{4}$$

Since the value of t_f is relatively small, it is ensured that the driver can better maintain the small fluctuations in acceleration near $d^2\Delta x_n(t + t_f)/dt^2$ in t_f after he is familiar with V2X equipment. At this time, the acceleration in the improved V2X model remains constant within the t_f time range. According to Newton's law of motion, the distance $\Delta x_n(t + t_f)$ between two vehicles considering t_f is expanded as Taylor, and acceleration term is reserved, which can be rewritten as

$$\Delta x_n\left(t + t_f\right) = \Delta x_n(t) + \frac{d\Delta x_n(t)}{dt} t_f + \frac{1}{2}\frac{d^2 x_n(t)}{dt^2} t_f^2. \tag{5}$$

Substituting equation (5) into the right side of equation (2), and deriving

$$\begin{aligned}\frac{d^2 x_n(t)}{dt^2} &= \alpha\left[V\left(\Delta x_n\left(t + t_f\right)\right) - \dot{x}_n(t)\right],\\ &= \alpha\left[V\left(\Delta x_n(t) + \frac{d\Delta x_n(t)}{dt} t_f + \frac{1}{2}\frac{d^2\Delta x_n(t)}{dt^2} t_f^2\right) - \dot{x}_n(t)\right],\\ &= \alpha\left[V(\Delta x_n(t)) + t_f V'(\Delta x_n(t))\frac{d\Delta x_n(t)}{dt} + \frac{t_f^2}{2} V'(\Delta x_n(t))\frac{d^2\Delta x_n(t)}{dt^2} - \dot{x}_n(t)\right].\end{aligned} \tag{6}$$

where $V'(\Delta x_n(t))$ is the derivative of the optimal velocity $V(x)$ at $x = \Delta x_n(t)$.

Setting $\gamma = \alpha t_f V'(\Delta x_n(t))$, and equation (2) can be rewritten as

$$\frac{d^2 x_n(t)}{dt^2} = \alpha\left[V(\Delta x_n(t)) - \dot{x}_n(t)\right] + \gamma\frac{d\Delta x_n(t)}{dt} + \frac{\gamma^2}{2\alpha V'(\Delta x_n(t))}\frac{d^2\Delta x_n(t)}{dt^2}. \tag{7}$$

By comparing equation (7) with the OV model, it can be found that the proposed improved V2X car-following model considers $\gamma(\mathrm{d}\Delta x_n(t)/\mathrm{d}t) + (\gamma^2/2\alpha V'(\Delta x_n(t)))\mathrm{d}^2\Delta x_n(t)/\mathrm{d}t^2$ term missed in the OV model, that is, the improved model emphasizes the effect of the state change of the following vehicle and the acceleration difference of the front one, and the traffic operation state will be affected by changes in the acceleration of the preceding vehicle.

3.3. State Analysis. In V2X environment, the driver pre-accelerates the vehicle n within t_f before the preceding vehicle starts according to real-time information regarding road environment. After vehicle n starts, vehicle $n+1$ follows according to equation (2). During t_f, there are three possible motion states for vehicle $n+1$.

3.3.1. State 1: Continuous Acceleration. When t_f is small, vehicle $n+1$ only perform pre-acceleration by using the difference $(h_0 - h_c)$ between the stopping distance h_0 and the safe distance h_c from the preceding vehicle n. Vehicle n starts before $\Delta x_n(t) = h_c$. In this state, when $t = t_f$,

$$\Delta x_n\left(t_f\right) \geq h_c. \tag{8}$$

The changes of velocity and headway of the two vehicles in state 1 is shown in Figure 2.

3.3.2. State 2: Accelerate First and Then Decelerate. With the increase of t_f, vehicle $n+1$ uses the difference $(h_0 - h_c)$ between the initial headway h_0 and the safe headway h_c from the preceding vehicle n to accelerate first, then decelerate when $\Delta x_n(t) = h_c\,(t < t_f)$, and the preceding vehicle n starts before vehicle $n+1$'s speed decreases to 0. In this state, when $t = t_f$,

$$\Delta x_n\left(t_f\right) < h_c. \tag{9}$$

The changes of velocity and headway of the two vehicles in state is shown in Figure 3.

3.3.3. State 3: Secondary Stopping. When vehicle $n+1$ accelerate first and then decelerate to the speed of 0, vehicle n has not start yet, then vehicle $n+1$ needs a second stop, and follows according to equation (2) after vehicle n starts. From equation (1), it can be known that when $V(\Delta x_n(t)) = 0$, $\Delta x_n(t) = 0$. Therefore, when $t = t_f$,

$$\Delta x_n\left(t_f\right) = 0. \tag{10}$$

The changes of velocity and headway of the two vehicles in state is shown in Figure 4. Owing to the limitations of the optimal velocity function, the speed will drop to zero suddenly.

4. Stability Analysis

The critical stability condition of the improving the V2X follower model is analyzed using the Lyapunov first method and combined with the linear harmonic perturbation method. If the heel-chase model meets this stability condition, then even if the vehicle constitutes.

The Lyapunov first method: If the system characteristic equations are linearized and the solutions are all negative real numbers or complex numbers with negative real parts, then the original system is not only stable and asymptotically stable, the system will not be unstable due to the neglected nonlinear terms; however, if there is a part of the solutions of the equations ignoring the nonlinear terms with zero real parts and the rest with negative real parts, the neglected nonlinear terms will have an impact on the stability of the system.

This section utilizes the linear stability theory to solve and analyze the neutral stability condition of the car-following model that takes t_f into account, to evaluate the impact of t_f on traffic stability. Assuming that the vehicles in the platoon are isomorphic, they all travel on the road with the same initial headway h_0 and speed $V(h_0)$. In the initial state, the transportation system is in a stable state, and the consistent steady-state solution of the model (2) is

$$x_n^{(0)}(t) = h_0 t + V\left(h_0\right)t. \tag{11}$$

If a small disturbance $y_n(t)$ is exerted to the traffic system at time t, the position $x_n(t)$ of vehicle n at time t under the influence of the disturbance can be expressed by the following equation:

$$x_n(t) = h_0 t + V\left(h_0\right)t + y_n(t). \tag{12}$$

Substituting equation (12) into equation (2), and the linearized equation about $y_n(t)$ can be obtained after simplification:

$$\frac{\mathrm{d}^2 y_n(t)}{\mathrm{d}t^2} = \alpha\left[V'\left(h_0\right)\Delta y_n\left(t+t_f\right) - \frac{\mathrm{d}y_n\left(t+t_f\right)}{\mathrm{d}t}\right]. \tag{13}$$

where $\Delta y_n(t) = y_{n+1}(t) - y_n(t)$. $V'(h_0)$ represents the derivative of the optimal velocity function $V(x)$ at $x = h_0$.

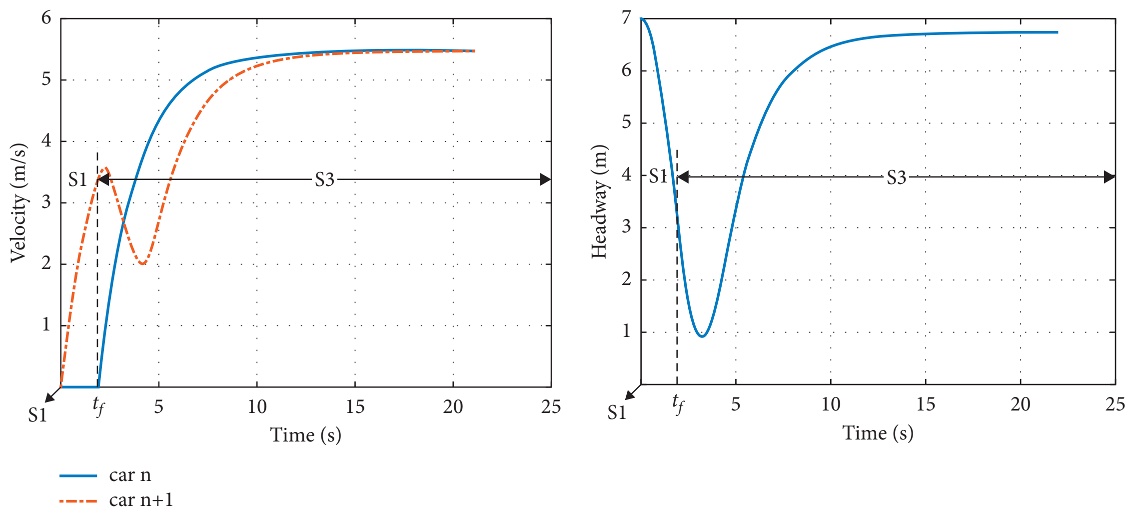
Setting $y_n(t) = e^{ikn+zt}$, i is the imaginary part of the complex number, k represents the safety factor, n represents the nth vehicle, z is the parameter assumed in the derivation and, expanding equation (13) to get the equation about z,

$$z^2 + \alpha z e^{zt_f} - \alpha V'\left(h_0\right)e^{zt_f}\left(e^{ik} - 1\right) = 0. \tag{14}$$

Expanding the z in equation (4) to $z = z_1(ik) + z_2(ik)^2 + \ldots$, reserving it to the second term of ik to get the following:

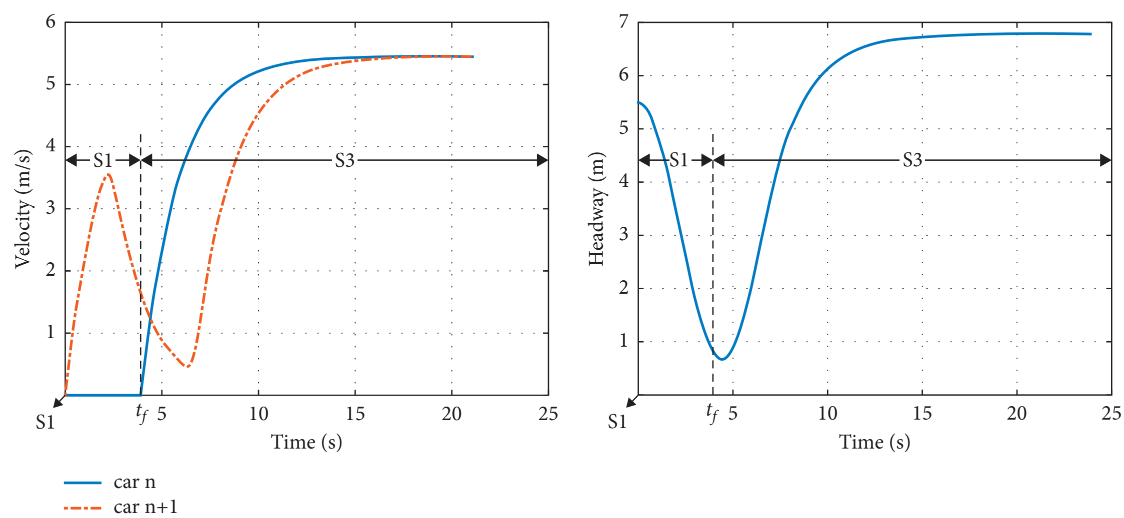
$$\begin{aligned} z_1 &= V'(h), \\ z_2 &= \frac{V'\left(h_0\right)}{2} - \frac{V'(h)^2}{\alpha}. \end{aligned} \tag{15}$$

When $z_2 > 0$, the transportation system will be in a stable state; on the contrary, when $z_2 < 0$, it will be in an unstable state. In unstable state, any small disturbance will make the transportation system tend to chaos. Therefore, the neutral stability condition of the improved V2X car-following model proposed in this paper is



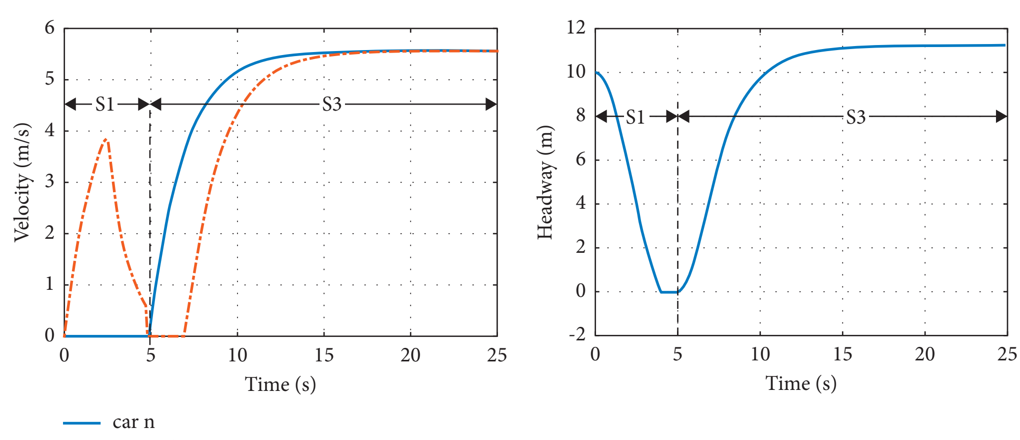
(a) (b)

Figure 2: Changes of the two vehicles' velocity and headway in state 1. (a) Velocity. (b) Headway.



(a) (b)

Figure 3: Changes of the two vehicles' velocity and headway in state 2. (a) Velocity. (b) Headway.



(a) (b)

Figure 4: Changes of the two vehicles' velocity and headway in state 3. (a) Velocity. (b) Headway.

$$\alpha_s = \frac{2V'(h_0)}{1 + 2V'(h_0)t_f}. \tag{16}$$

When $t_f = 0$, that is, ignoring the influence of the driver's early reaction on the traffic flow, the neutral stability condition of the improved V2X car-following model is

$$\alpha_s = 2V'(h_0). \tag{17}$$

It is consistent with the neutral stability condition of the OV model, which is in line with the modeling idea of improving the V2X car-following model. When $\alpha_s > 2V'(h_0)/1 + 2V'(h_0)t_f$, traffic system is in a stable state and can withstand the impact of small disturbances by deriving the neutral stability conditions of the improved V2X car-following model. Otherwise the system will be in an unstable state, and the impact of small disturbances will cause it to be in an unstable state.

The influence diagram of the driver's early reaction time t_f on the stability of the traffic system is drawn. At the same time, other conditions remain unchanged, and the value of the arbitrary parameters is changed in the improved V2X car-following model (this section chooses to change the parameter $v_{\max}$). The change trend of the traffic system sensitivity α with different t_f is plotted, and the influence of the change of the model parameters on the stability of the traffic system by t_f is compared and analyzed. The parameters and their values in the simulation are summarized as shown in Table 1. Figure 5 shows the neutral stability curve.

Each curve in Figure 5 has a critical vertex, and its coordinates is (h_c, α_c), $\alpha_c = v_{\max}/1 + v_{\max}t_f$. The traffic flow in the area above the curve is stable; while that in the area under the curve is relatively unstable, possibly leading to traffic wave propagation, traffic jams, traffic accidents, etc. When $t_f = 0$, the obtained critical point and the neutral stability curve are the corresponding ones of the OV model, respectively.

As shown in Figure 5, as t_f increases, the traffic system tends to be stable. This shows that the driver's early reaction to traffic flow changes has a positive effect on maintaining traffic stability. At the same time, with the increase of t_f, the positive effect of the unit advance reaction time on the stability of traffic flow gradually decreases. To a certain extent, it shows that the value of t_f should be appropriate, not excessive pursuit of traffic benefits.

By comparing the subgraphs in Figure 5, it can be seen that when $v_{\max}$ increases, the traffic flow obviously tends to be more unstable, and the positive effect of increasing t_f on the stability of the traffic flow is more evident.

5. Simulation Analysis

A simulation analysis of the car-following behavior of queuing vehicles stopping to wait in front of the intersection was conducted in this section to analyze the impact of the proposed improved V2X car-following model on the traffic flow dissipation at signalized intersections. There are 5 vehicles in vehicle queue, and the time when the green light is on is represented by g_0. Under the condition of satisfying the basic characteristics of the car-following behavior, the following basic assumptions are designed for the distribution and movement of the vehicles to make the simulation more feasible:

(1) The vehicle may be regarded as a particle during the simulation process
(2) In the vehicles' queuing up, any two adjacent vehicles have the same stopping distance
(3) All vehicles in the platoon have the same acceleration/deceleration performance and maximum driving speed
(4) When the acceleration value of each vehicle in the platoon is restored to 0, the traffic flow is deemed to be steady
(5) All drivers in the platoon need cooperation

In microscopic traffic flow studies, initial headway, safe headway and maximum speed are all indicators for studying vehicle following behavior, and these indicators all fit with the parameters studied in our model, so the simulation experiments that follow control and study such parameters. The parameter value can be referred to literature [30]. All simulation parameters and their corresponding values in the simulation are summarized in Table 2.

5.1. Influence of Different Advance Reaction Time on Vehicle Operation Parameters.

The simulation aims to measure the influence of drivers' different response advance time t_f on the speed, acceleration and head distance of each vehicle in the platoon. $t_{f\max}$ represents the driver's critical advance reaction time. When $t_f > t_{f\max}$, the following vehicle will accelerate first, then decelerate, and stop for the second time and so on. Parameters and their values in the simulation are summarized in Table 3.

The initial parameter values are substituted into the improved V2X car-following model, and one significant digit after the decimal point is reserved to obtain $t_{f\max} = 3.9$ s. Taken $t_{f\max}$ as the median time, and two sets of time are taken with 0.5 s before and after to simulate the motion state changes of each vehicle in the platoon in the five groups of time. The simulation results are shown in Figure 6.

The simulation results are analyzed from three aspects: the acceleration time of the vehicles in the platoon, the stabilization time of the platoon system, and the minimum headway of the vehicles in the platoon. Conclusions of the analysis are obtained as follows:

(1) The acceleration time of following vehicles increases with the increase of t_f according to the acceleration time of vehicles in the platoon, which indicates that the earlier drivers can obtain the change of traffic flow status, the more they can manipulate vehicles in advance, changing the traffic state.
(2) From the perspective of the stability time of the platoon system, the stability time of the traffic system decreases first and then increases with the advance

Table1: Parameters and values.

Parameters	Values
Safe headway, h_c	4 (m)
Driver's early reaction time, t_f	0, 0.2, 0.5, 1, 1.5 (s)
Maximum velocity, $v_{\max}$	15, 30, 45, 60 (km/h)

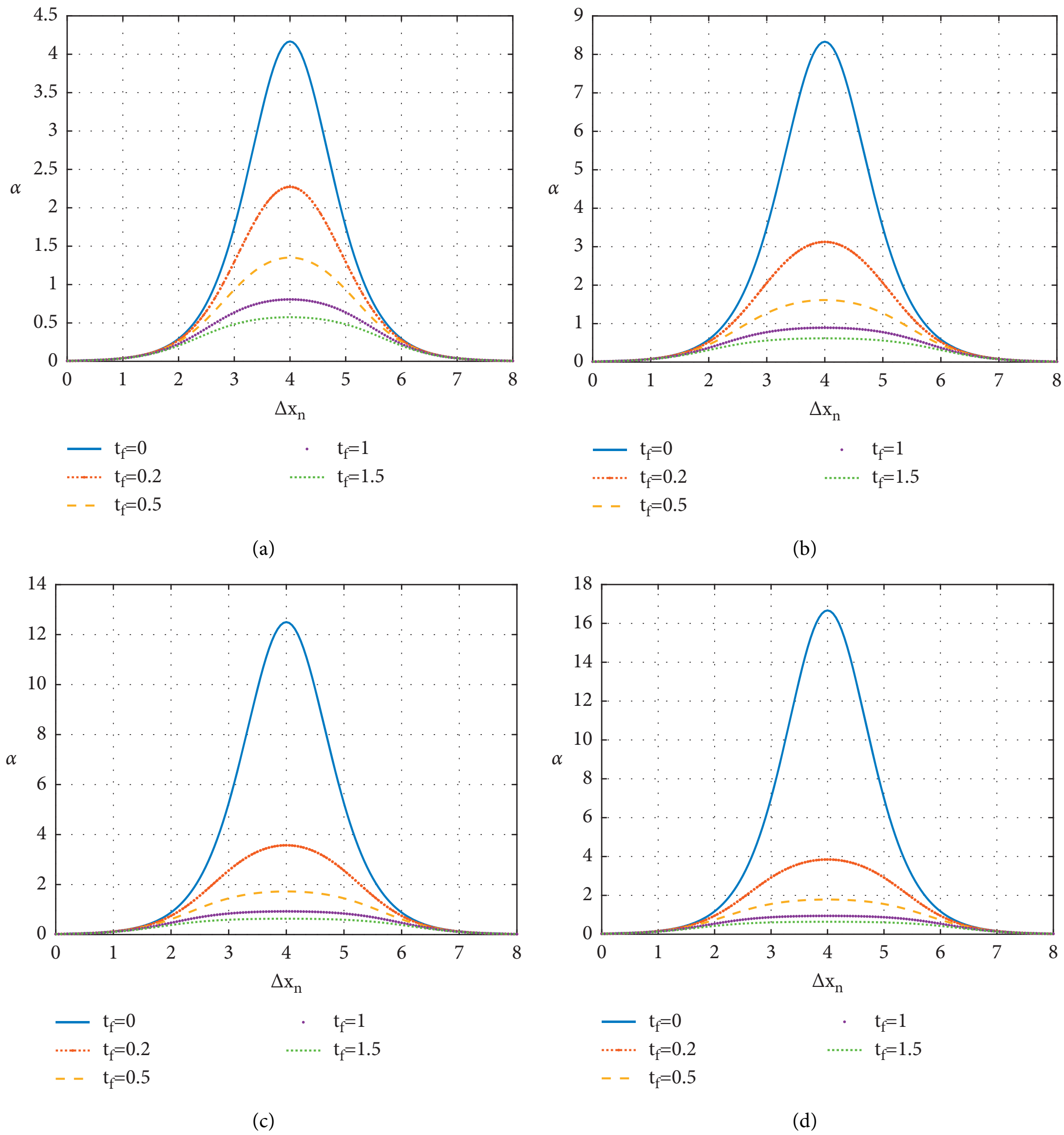


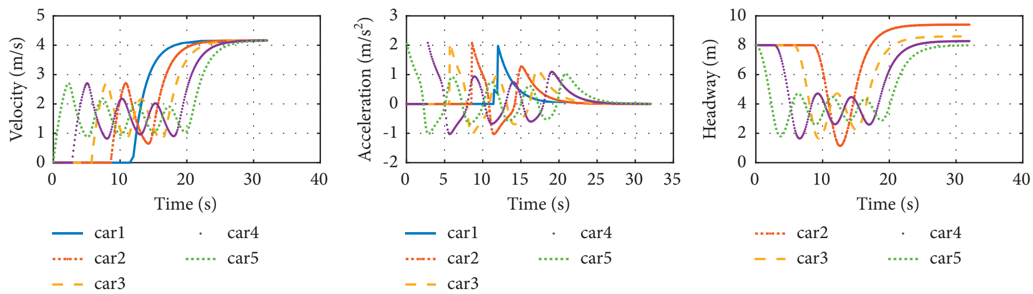
Figure 5: Neutral stability curve with different advance reaction times. (a)$v_{\max} = 15$ km/h. (b)$v_{\max} = 30$ km/h. (c)$v_{\max} = 45$ km/h. (d)$v_{\max} = 60$ km/h.

Table 2: Simulation environment parameters and values.

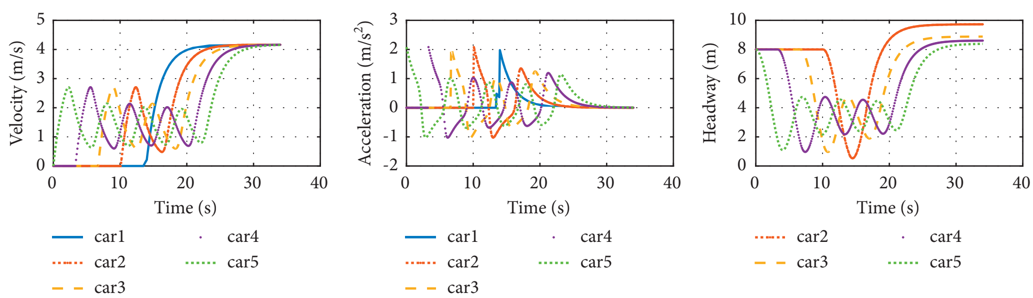
Parameters	Values
Sensitivity, α	0.5
Distance between head car and stop line	0.5 (m)
Initial headway, $\Delta x_n(0)$	6, 7, 8, 10 (m)
Safe headway, h_c	2, 3, 4 (m)
Maximum velocity, $v_{\max}$	10, 15, 20 (km/h)

Table 3: Simulation parameters and their values with different t_f.

Parameters	Values
Sensitivity, α	0.5
Distance between head car and stop line	0.5 (m)
Initial headway, $\Delta x_n(0)$	7 (m)
Safe headway, h_c	4 (m)
Maximum velocity, $v_{\max}$	15 (km/h)
Advance reaction time, t_f	2.9, 3.4, 3.9, 4.4, 4.5 (s)



(a)



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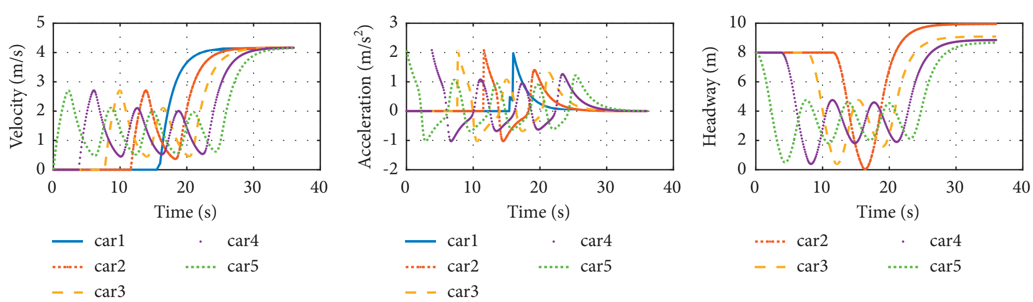
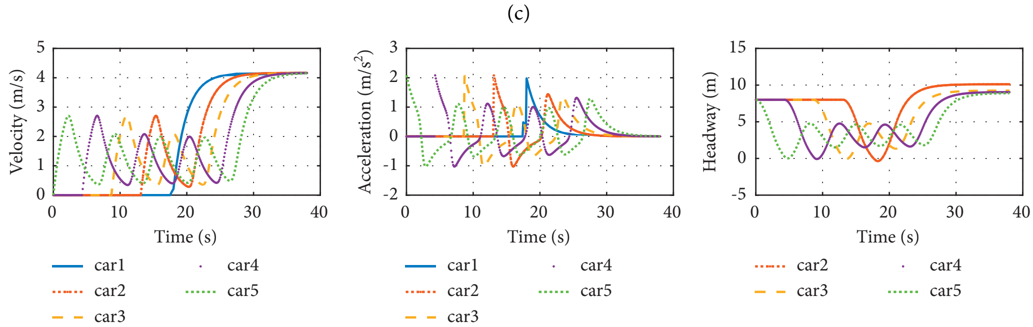


(c)



(d)

Figure 6: Continued.

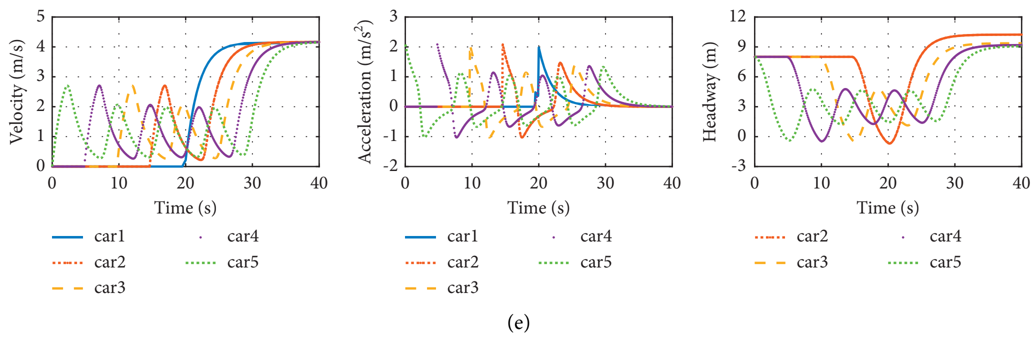


FIGURE 6: Motion state changes of each vehicle at different advance reaction times. (a)$t_f = 2.9$ s. (b)$t_f = 3.4$ s. (c)$t_f = 3.9$ s. (d)$t_f = 4.4$ s. (e)$t_f = 4.9$ s.

reaction time increasing after the green light starts. Drivers can have enough time to change the speed and the accelerated speed after considering the driver's reaction time. Therefore, the platoon has a small forward starting wave speed before the green light is on. When the green light is on, the traffic system can quickly return to a stable state. However, after the driver's advance reaction time reaches at the critical value, if the advance reaction time continues to increase, the vehicle will accelerate first, then decelerate, and stop for the second time, etc. At this time, the platoon system is extremely unstable, and the time for the platoon system to restore stability increases.

(3) From the perspective of the minimum headway between adjacent vehicles in the advance reaction state, the minimum headway gradually decreases with the increase of the advance reaction time. The driver's reaction time increases, accordingly, the driving time in the early reaction state becomes longer, and the distance traveled increases. Therefore, the minimum headway between vehicles gradually increases before the green light is on. When $t_f = t_{f\max}$, the minimum headway is closest to 0 (greater than 0).

To sum up, the car-following model considering t_f has a positive effect on the stability of traffic system. When $t_f < t_{f\max}$, the promotion effect increases with the increase of the advance reaction time; while When $t_f > t_{f\max}$, the vehicle queue system tends to be unstable with the increase of the advance reaction time.

5.2. The Effect of the Initial Headway on the Advance Reaction Time and Vehicle Operation Data. Different from vehicle queue typically lining up in front of intersections, the driver can start the vehicle in advance by using the initial headway $\Delta x_n(0)$. With the help of complete road traffic information in V2X environment, this section aims to study the influence of different initial headway $\Delta x_n(0)$ on the driver's advance reaction time t_f and the operation parameters of each vehicle in the platoon. The parameters and their values in the simulation are summarized as shown in Table 4.

TABLE 4: Simulation parameters and values with different initial headway.

Parameters	Values
Sensitivity, α	0.5
Distance between head car and stop line	0.5 (m)
Initial headway, $\Delta x_n(0)$	6, 8, 10 (m)
Safe headway, h_c	4 (m)
Maximum velocity, $v_{\max}$	15 (km/h)

The critical reaction advance time is calculated with different initial headway $\Delta x_n(0)$, then the maximum velocity of the vehicle in pre-acceleration status is simulated, as well as the speed, accelerated speed and headway of each single vehicle in the platoon. The results are shown in Table 5 and Figure 7.

(1) The simulation results are analyzed in terms of the maximum speed that vehicles in the platoon can reach in the pre-acceleration status, to learn that the value is positively correlated with $\Delta x_n(0)$. The reason is that the larger the $\Delta x_n(0)$ is, the longer distance drivers can obtain to pre-accelerate the vehicle during the early start phase, so the speed reached during the early start phase is greater.

(2) The simulation results are analyzed regarding the maximum advance reaction time, and it can be seen that the value is not only related to $\Delta x_n(0)$, but also the maximum speed reached during the early start phase. According to the law of kinematics: distance equals speed multiplied by time. The former analysis results tell that the maximum speed reached in the early start phase is positively correlated with $\Delta x_n(0)$, at this time, time and distance are negatively correlated. But at the same time, the larger $\Delta x_n(0)$ is, the longer distance drivers can react in advance, and the larger the t_f is. Therefore, $t_{f\max}$ is relevant to the maximum speed and $\Delta x_n(0)$ that the vehicles in the platoon can reach during the early per-acceleration status.

5.3. The Effect of the Maximum Speed on the Advance Reaction Time and Vehicle Operation Data. It can be seen from equation (3) that $v_{\max}$ is an important factor to restrict

Table 5: The effect of different initial headway in pre-acceleration status.

Initial headway, $\Delta x_n(0)$ (m)	Critical reaction advance time, $t_{f\max}$ (s)	Maximum vehicle speed (m/s)
10	4.1	3.1042
8	3.9	2.7048
6	4.8	2.0309

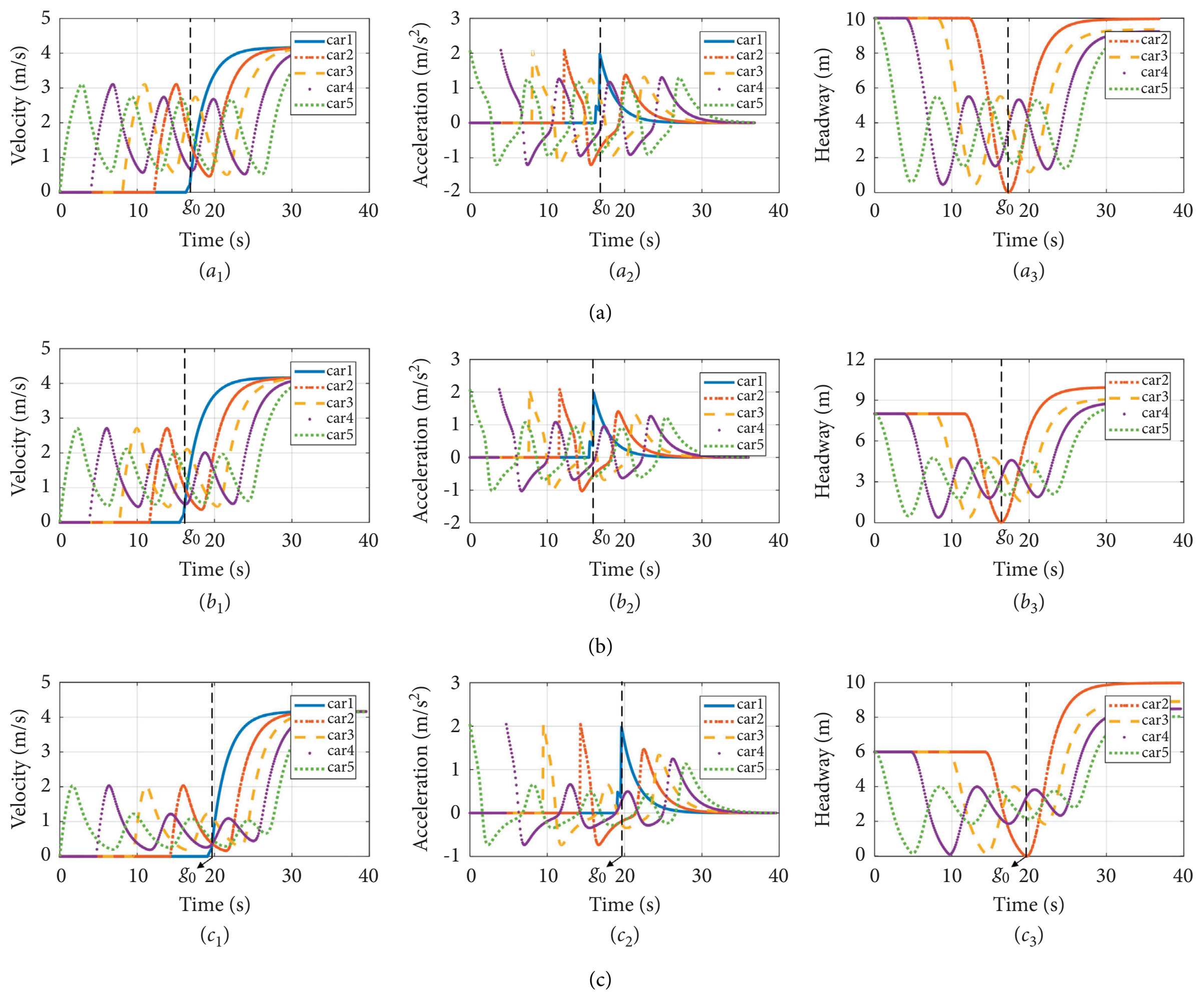


Figure 7: Vehicle parameters changes in the platoon with different initial headway. (a)$\Delta x_n(0) = 10$ m, $t_{f\max} = 4.1$ s. (b)$\Delta x_n(0) = 8$ m, $t_{f\max} = 3.9$ s. (c)$\Delta x_n(0) = 6$ m, $t_{f\max} = 4.8$ s.

the optimal speed. This section highlights the influence of different maximum speeds $v_{\max}$ on the advance reaction time t_f and the operation parameters of the vehicles in the platoon. The parameters and corresponding values in the simulation are illustrated in Table 6.

The critical advance reaction time $t_{f\max}$ is calculated at different maximum speeds $v_{\max}$. The maximum speed of vehicles at different $v_{\max}$ in the pre-acceleration status is simulated, along with the speed, accelerated speed, and headway changes of each vehicle in the platoon. The results are displayed in Table 7 and Figure 8, respectively.

Combined with the analysis of Table 7 and Figure 8, the following can be concluded:

(1) The maximum velocity of the vehicle during the pre-acceleration status increases with the increase of $v_{\max}$. The higher the design speed is, the greater the acceleration intensity of the vehicle is, so the maximum speed reached during the pre-acceleration stage.

(2) The intensity of acceleration and deceleration of accelerated speed increases with the increase of $v_{\max}$. When $v_{\max}$ increases, the driver has larger space to change the speed of the vehicle, so the acceleration change range increases.

(3) $t_{f\max}$ is inversely proportional to the maximum speed reached during the pre-acceleration phase.

Table 6: Simulation parameters and values with different maximum speed.

Parameters	Values
Sensitivity, α	0.5
Distance between head car and stop line	0.5 (m)
Maximum velocity, $v_{\max}$	10, 15, 20 (km/h)
Initial headway, $\Delta x_n(0)$	7 (m)
Safe headway, h_c	4 (m)

Table 7: The effect of different maximum speeds on early start.

Safe headway, h_c (km/h)	Critical reaction advance time, $t_{f\max}$ (s)	Maximum vehicle speed (m/s)
10	8.8	1.8153
15	4	2.4177
20	2.9	2.9452

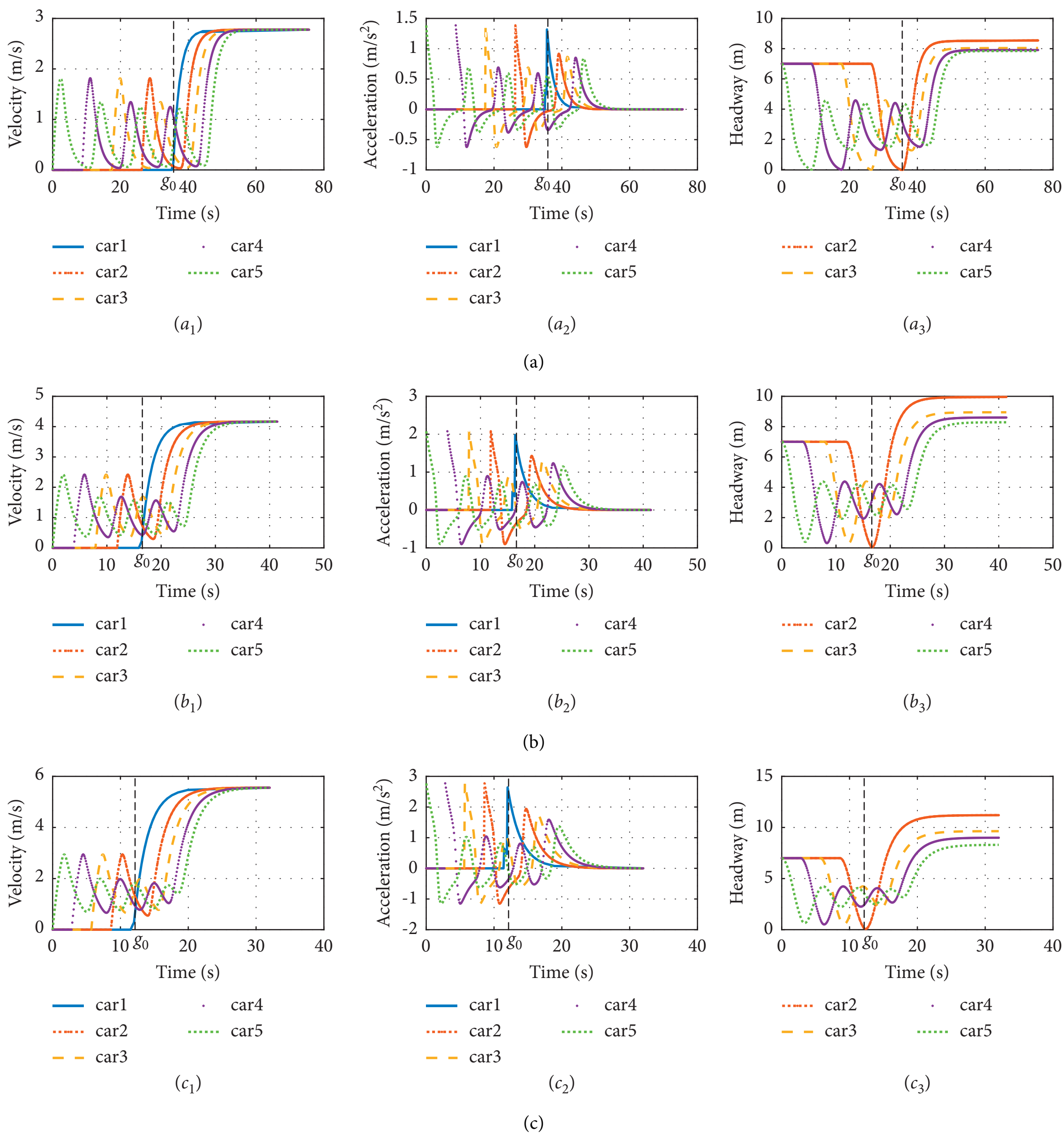


Figure 8: Vehicle parameters changes in the platoon with different maximum speeds. (a)$v_{\max} = 10$ km/h, $t_{f\max} = 8.8$ s. (b)$v_{\max} = 15$ km/h, $t_{f\max} = 4.3$ s. (c)$v_{\max} = 20$ km/h, $t_{f\max} = 2.9$ s.

When $\Delta x_n(0)$ is fixed, the higher the vehicle speed in the pre-acceleration phase, the shorter the early reaction time.

When $v_{\max}$ is designed as 10 km/h, $t_{f\max}$ is 8.8 s, and the maximum speed reached during the pre-acceleration phase is 1.8153 m/s. In this case, the driver's advance reaction time is sufficient and enough, but the speed of the vehicle is quite low, which is a necessary condition for the vehicle to pass the red light without stopping.

5.4. The Effect of Safe Headway between Vehicles on Advance Reaction Time and Vehicle Operation Data. Before the light turns green, drivers of the Internet connected vehicles use the headway $\Delta x_n(t)$ to manipulate vehicles in advance. The acceleration distance is the headway minus the safe distance. When the headway is less than the safe distance, the driver begins to slow down. This section focuses on the impact of different safe headway h_c on advance reaction time t_f and the operation parameters of each vehicle in the platoon. The parameters and their values in the simulation are summarized in Table 8.

The critical advance reaction time is calculated at different maximum speeds. The maximum speed of vehicles at different maximum speeds in the early start phase is simulated, as well as the speed, accelerated speed, and headway of each vehicle in the platoon. The results are shown in Table 9 and Figure 9, respectively.

By comparing and analyzing the subgraphs in Figure 9 with Table 9, the following can be concluded:

(1) The maximum speed reached in preacceleration status is inversely proportional to h_c, and $t_{f\max}$ is directly proportional to h_c. When $\Delta x_n(0)$ is fixed, the smaller the safe distance, the longer the acceleration section the vehicle passes. Therefore, the greater the maximum speed can be reached, the shorter the maximum time for early reaction.

(2) The intensity of acceleration and deceleration of the Internet connected vehicles increases with the decrease of h_c in pre-acceleration stage. With the decrease of h_c, the longer the acceleration section the driver can control, the larger the acceleration change range.

(3) When the light turns green, the headway of the platoon will decrease with the decrease of h_c after the traffic flow is stable.

From Figure 9, it can be found that after green light is on, the distance between the headway of the following vehicles gradually increases and tends to be constant with the time progressing. However, the headway of the second vehicle after stabilization is larger than that of other following vehicles, and the difference increases with the decrease of the safe distance. The main reason for this phenomenon is the limitation of the optimal velocity function. This is mainly reflected in the fact that the optimal velocity fails to reach the maximum speed with the decrease of the safe headway. After green light is turned on, the head vehicle possesses a larger headway and has no limit to the safe distance. According to the characteristics of the optimal velocity function, the head vehicle can run at the maximum speed. However, a speed difference still exists between the second vehicle and the head one after the traffic flow is stable, so the headway of the second vehicle is longer than that of other behind following cars. The variation trend of the optimal velocity function values with different safe distance is simulated to explain the above simulation results. The simulation results are shown in Figure 10.

5.5. Analysis of Dissipation Performance of the Platoon. In order to solve the problem that the Newell model is not applicable when dealing with vehicle starting acceleration at traffic signal intersections, scholars extended the Newell model and retained it to the second term by using Taylor formula, and proposed an Optimal Velocity model .In the traffic dynamics, time delay is a critical parameter which was recognized in traffic studies. Time delay may have a significative effect upon the property of traffic flow. The improved OVD model developed considering the driver response delay time represents the driver's instantaneous response to the stimulus of the vehicle in front.

To measure the performance of the proposed improved V2X car-following model considering the driver's advance reaction time, this section analyzes the typical OV model, the OV model considering the reaction delay, and the improved V2X car-following model proposed in this paper to dissipate the vehicle queue at intersections. t_w means the time when the traffic flow system returns to stability after the green light is on. The criterion of the traffic flow stability recovery adopts that the acceleration of each vehicle in the platoon defined above returns to 0. The simulation parameters and their values are shown in Table 10.

After the green light is on, the variation of the speed and accelerated speed of the vehicles in the three models of the platoon are simulated, obtaining the dissipation evolution process of the three models as shown in Figure 11.

It can be seen from Figure 11 that the platoon system achieves stability in the improved model proposed in this paper faster than that in the other two models based on the time when the light turns green. To compare the data intuitively, the statistics of time when the platoon reaches the stability based on different models after the light turning green are shown in Table 11.

As is shown in Table 11, after the green light is on, the platoon stability recovery time in the improved V2X car-following model increases by 13.55% compared with that in the traditional OV model, while by 40.6% compared with that in the OV model considering the reaction delay.

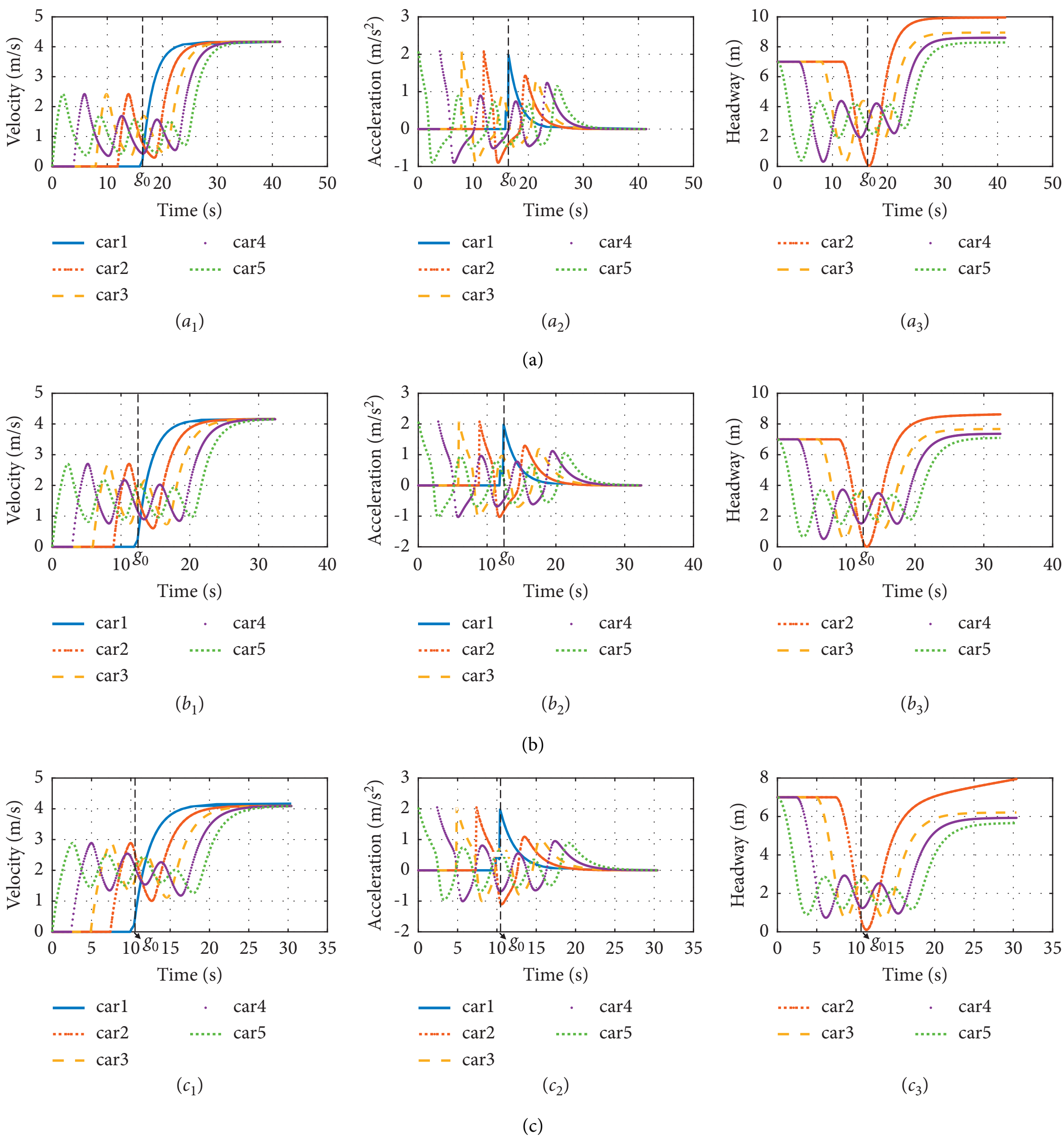


Figure 9: Vehicle parameters changes in the platoon with the different safe distance. (a)$h_c = 4$ m, $t_{f\max} = 4$ s. (b)$h_c = 3$ m, $t_{f\max} = 3$ s. (c)$h_c = 2$ m, $t_{f\max} = 2.5$ s.

Table 8: Simulation parameters and corresponding values with different safety distance.

Parameters	Values
Sensitivity, α	0.5
Safe headway, h_c	2, 3, 4 (m)
Distance between head car and stop line	0.5 (m)
Maximum velocity, $v_{\max}$	15 (km/h)
Initial headway, $\Delta x_n(0)$	7 (m)

Table 9: The effect of different safety distance on early start.

Safe headway, h_c (m)	Critical reaction advance time, $t_{f\max}$ (s)	Maximum vehicle speed (m/s)
4	4	2.4177
3	3	2.7005
2	2.5	2.8894

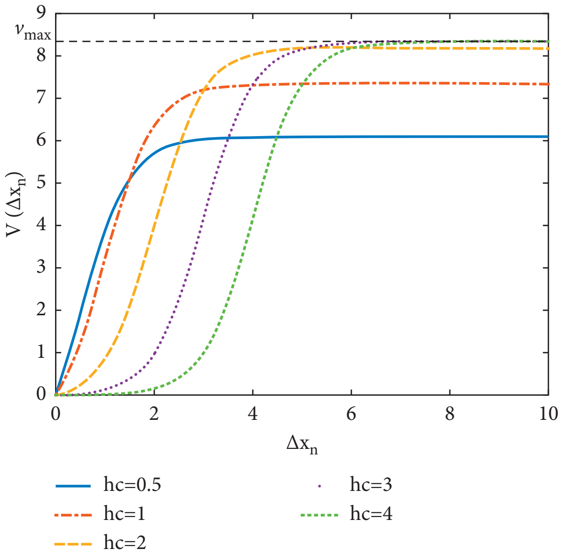
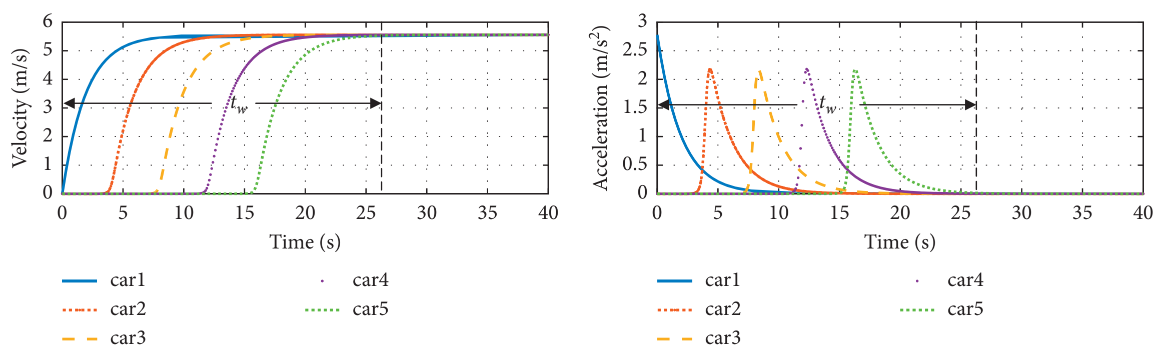


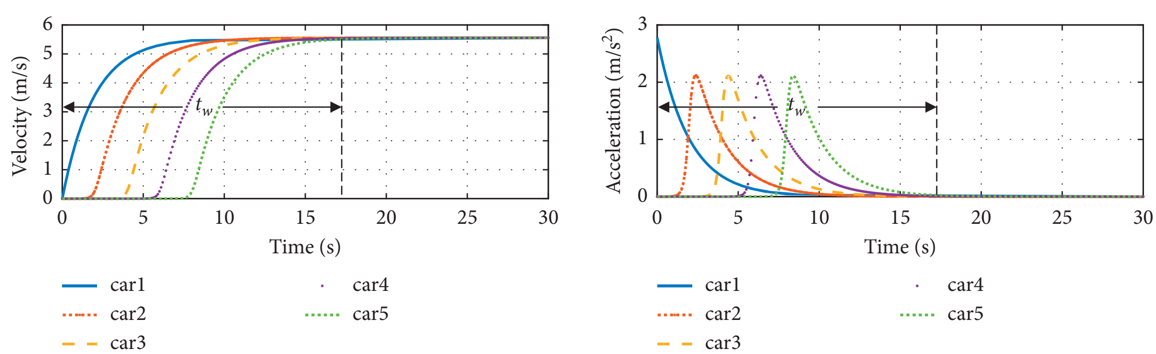
Figure 10: Optimal velocity variation with different safe distance.

Table 10: Values of each parameter in the model.

Parameters	Values
Sensitivity, α	0.5
Safe headway, h_c	4 (m)
Distance between head car and stop line	0.5 (m)
Maximum velocity, v_{max}	20 (km/h)
Initial headway, $\Delta x_n(0)$	8 (m)
Advance reaction time, t_f	2 (s)
Reaction delay time, t_d	2 (s)

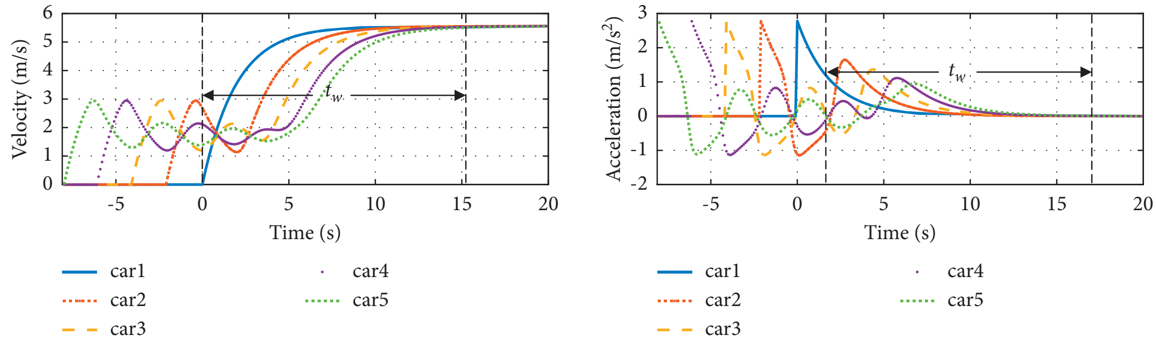


(a)



(b)

Figure 11: Continued.



(c)

Figure 11: Evolution process of queue dissipation with different car-following models. (a) OV model considering driver's reaction delay. (b) OV model. (c) Improved V2X car-following model.

Table 11: The time of the platoon stability recovery under different models.

Model	Time (s)
OV model considering driver's delayed reaction	26.1
OV model	17.6
Improved V2X car-following model	15.5

6. Conclusions

This paper establishes an improved V2X car-following model considering the driver's advance reaction time t_f in V2X environment. The impact of different t_f on traffic flow at intersections is studied, and the critical advance reaction time $t_{f\max}$ is analyzed along with different initial headway, maximum speed, safe distance and their respective effects on traffic flow. Eventually, the effectiveness of the model is verified through simulation analysis. The research results in this paper show the following:

(1) The proposed improved V2X car-following model has a positive effect on the stability of traffic flow. The stability analysis of the model found that with the increase of t_f, the operation of the traffic flow becomes more and more stable.

(2) The proposed improved V2X car-following model can improve the dissipation efficiency of the intersection team. Before reaching the critical reaction time $t_{f\max}$, with the increase of t_f, the efficiency of restoring stability of the traffic flow system at intersections is significantly improved after the green light is on. The longer the initial headway, the higher the maximum speed reached during the early start state. Under the same conditions, t_f is inversely proportional to $v_{\max}$; while the maximum speed reached during the early start phase is directly proportional to $v_{\max}$.

(3) The proposed improved V2X car-following model has an upper limit on t_f. Through the analysis of the simulation results, we found that the value of aa is different under different initial traffic conditions. When $t_f > t_{f\max}$, the traffic flow system is extremely unstable, so $t_f \le t_{f\max}$ should be satisfied within the recommended response time for the driver.

Compared with the typical OV model and the OV model considering the reaction delay, the model proposed in this paper greatly enhances the efficiency of traffic flow recovery after the green light is on. Therefore, the model proposed in this paper can promote the stability of traffic flow, and it is necessary to think over this model for solving traffic congestion and raising the traffic efficiency at intersections.

However, all set conditions are ideal when simulation verification is performed, quite different from the actual situation. In the construction of the simulation environment, the calibration of the parameter values is based on the possible values used in previous studies, and the sensitivity coefficient α is taken as a constant value in the simulation process, and assuming the same advance reaction time of the drivers in the fleet, the follow-up can consider the different early reaction times of drivers in different vehicles for in-depth study. And, this paper only focuses on the driver's driving behavior, and the subsequent study can also be carried out for traffic safety. In reality, the influence of lateral vehicles on drivers exists in front of intersections, and packet loss of information transmission data is a frequent phenomenon based on V2X devices at this stage. These three factors can be considered for in-depth study on the basis of this paper.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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