

Research Article

Risk Modeling and Quantification of a Platoon in Mixed Traffic Based on the Mass-Spring-Damper Model

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Connected and automated vehicle (CAV) technologies have great potential to improve road safety. However, an emerging type of mixed traffic flow with human-driven vehicles (HDVs) and CAVs has also arisen in recent years. To improve the overall safety of this mixed traffic flow, a novel car-following model is proposed to control the driving behaviors of the above two types of vehicles in a platoon from the perspective of a mechanical system, mass-spring-damper (MSD) system. Furthermore, a quantitative index is proposed by incorporating the psychological field theory into the MSD model. The errors of spacing and speed in the car-following processes can be expressed as the accumulation of the virtual total energy, and the magnitude of the energy is used to reflect the danger level of vehicles in the mixed platoon. At the same time, the optimization model of minimum total energy is solved under the constraints of vehicle dynamics and the mechanical characteristics of the MSD system, and the optimal solutions are used as the parameters of the MSD car-following model. Finally, a mixed platoon composed of 3 CAVs and 2 HDVs without performing lane changing is tested using the driver-in-the-loop test platform. The test results show that, in the mixed platoon, CAVs can optimally adjust the intervehicle spacing by making full use of the braking distance, which also provides sufficient reaction time for the driver of HDV to avoid rear-end collisions. Furthermore, in the early stage of the emergency braking, the spacing error is the dominant factor influencing the car-following behaviors, but in the later stage of emergency braking, the speed error becomes the decisive factor of the car-following behaviors. These results indicate that the proposed car-following model and quantitative index are of great significance for improving the overall safety of the mixed traffic flow with CAVs and HDVs.

1. Introduction

Due to the slow expansion of the road network, traffic oscillations, and traffic accidents occur frequently in road traffic. The emerging connected and automated vehicle technologies, however, offer great potential for enhancing traffic operations and improving the roadway capacity under existing road infrastructure, which helps make traffic flow more stable, more efficient, and safer. This is because CAVs are able to share driving information with others in real time, which makes the motion of CAVs more cooperative [1]. Vehicle platooning is a typical application that stands out in the domain. Thus, it has obtained extensive research

interests and a great variety of research is indicating that platooning of CAVs can tremendously improve traffic safety [2–5] and energy efficiency [6]. It is worth noting that most research is focusing on the pure platoon of CAVs, but CAVs and HDVs will coexist in the near future [7–10]. Therefore, the most likely formation of vehicular platoons will be a mixture of CAVs and HDVs. This complex traffic environment will bring huge challenges to traffic flow modeling, control, and management when considering the stochastic driving characteristics of humans and the uncertainty of the interaction between CAVs and HDVs. Thus, how to make these two types of vehicles operate coordinately is the key to enhance traffic safety.

Modeling the mixed traffic flow is a feasible way to solve this problem. Many scholars have carried out in-depth research on the car-following models of vehicular platoons, which are mainly divided into the following categories: stimulus-response models [11], safety distance models [12], psycho-physical models [13], artificial intelligence model [14], optimal velocity model [15], intelligent driver model [16], and cellular automata model [17]. The advantages of these car-following models have been widely recognized in the field of transportation. More recently, some researchers have proposed car-following models combined with two different models to capture the driving behaviors of CAVs and HDVs, respectively. For example, Gong et al. [8] proposed a cooperative control method for mixed platoons to ensure the stability and safety of the platoons. In addition, the CAVs and HDVs adopted the MPC model and Newell model, respectively. The results indicate that this novel platoon control method can dampen traffic oscillation propagation and stabilize the traffic flow more efficiently for the entire mixed platoon. Zhu et al. [9] proposed a novel car-following model with adjustable sensitivity and smoothing factor for mixed traffic flow. The car-following model of HDVs selected optimal velocity model (OVM), while the car-following model of CAVs reduced its sensitivity factor on the basis of OVM. The numerical simulation results show that the proposed model is able to stabilize the mixed traffic flow and suppress the traffic jam. Zhao et al. [18] proposed a cooperative eco-driving model for mixed platoons, where HDVs were modeled by the OVM and CAVs are controlled by the MPC model. This model achieves better performance for the overall traffic. In these above-mentioned research studies, HDVs and CAVs used different car-following models under the mixed traffic environment, and they have achieved good results in improving mixed traffic efficiency and safety to a certain extent. However, the stochastic vehicle performance and driving behavior of CAVs and HDVs are not considered and employing two models will make the control system more complicated. Furthermore, it is uncoordinated for an integrated platoon system to use two different models to capture the motion of vehicles in the mixed platoon.

Furthermore, considering the similarity between the acceleration or deceleration behavior in traffic flow and the scaling properties of spring [19], some scholars modeled the traffic flow from the perspective of a mechanical system—the mass-spring (MS) system. For instance, Wang et al. [20] established a car-following model by regarding both the stopping (deceleration) process and the starting (acceleration) process as spring systems. Compared with traditional stimulus-response car-following models, the proposed model can better explain traffic flow phenomena and drivers' behavior. In the actual car-following process, the relative spacing and speed of two adjacent vehicles are two important indices. Therefore, some scholars applied the MSD theory to describe the interaction between vehicles in a platoon [21–23], and the MSD model was capable of enhancing traffic safety and increasing roadway capacity. However, all the proposed MSD models were only applicable

to the platoons that are entirely made up of HDVs or CAVs. Because the MSD system has natural stability characteristics and is widely used to represent interactions with uncertain environments [24], we propose a novel car-following model for the mixed platoon under the same simplified framework based on the virtual MSD theory, which has a great advantage over the traditional platoon model in both the stability analysis and the stable operation. Unlike the previous models, both HDVs and CAVs share the identical framework in the proposed model and it takes both the spacing errors and speed errors into account, which can more accurately describe the car-following behaviors of CAVs and HDVs.

Another problem of traffic flow is how to quantify the level of risk in car-following processes, which has a significant impact on driving behaviors. K. Vogel [25] compared with two safety indices “time headway (TH)” and “time to collision (TTC)” in different traffic situations. However, when the speed of the following vehicle is near or equal to that of the preceding vehicle, TTC changes sharply; when the speed of the preceding vehicle changes relatively large, TH will underestimate the danger of the car-following process. In other words, it is insufficient for TTC and TH to quantify the risk level of car-following. Lu et al. [26] proposed safety margin (SM) as a suitable quantitative index of risk perception based on the risk homeostasis theory. Compared with TTC and TH, SM more suitably quantifies the level of risk in car-following processes. Inspired by it, in this manuscript, combining with the psychological field theory, we utilize the magnitude of virtual total energy as a quantitative index of danger in the car-following processes based on the MSD car-following model.

The remainder of this paper is organized as follows: Section 2 presents the modeling, car-following rules, and spacing policy of a mixed vehicular platoon. Section 3 presents a novel car-following model of mixed platoons from the perspective of a mechanical system, and the string stability of the mixed platoon is analyzed based on the MSD model. In Section 4, the virtual total energy is proposed as a quantitative index based on the psychological field theory and MSD model to reflect the danger level of vehicles in the car-following processes. The optimization model of minimum total energy is solved under the constraints of vehicle dynamics and the mechanical characteristics of MSD system in Section 5. In Section 6, a mixed platoon is tested in the driver-in-the-loop test platform to verify the validity of the proposed MSD car-following model. Finally, conclusions are made.

2. Control of Vehicular Platoon

2.1. Modeling of Mixed Platoon. As shown in Figure 1, a mixed platoon consisting of n cars travels on the highway in a single lane, where the i^{th} vehicle is a HDV. In this platoon, x_i is the position of the i^{th} vehicle and v_i is the speed of the i^{th} vehicle. Therefore, for the i^{th} vehicle, the spacing errors can be defined as

$$\delta_i = x_{i-1} - x_i - L - d_s, \quad (1)$$

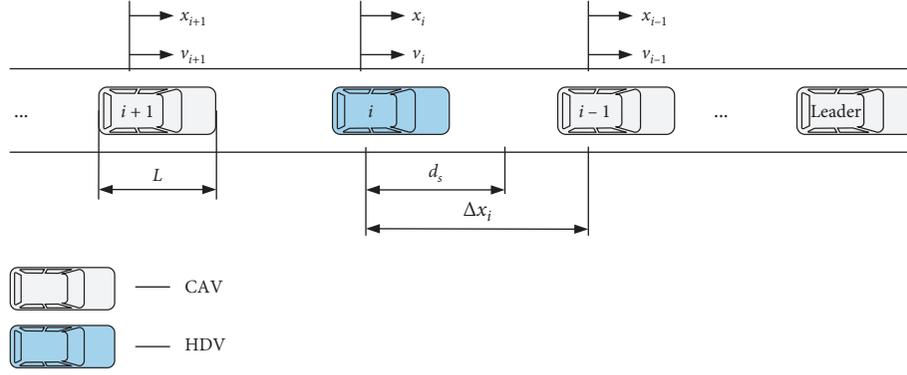


FIGURE 1: Model of a mixed platoon.

where L denotes the length of the vehicle and d_s represents the desired distance between the i^{th} and $i-1^{\text{th}}$ vehicles.

The kinematic differential equation of the intervehicle spacing error is

$$\dot{\delta}_i = \dot{x}_{i-1} - \dot{x}_i - \dot{d}_s = v_{i-1} - v_i - \dot{d}_s. \quad (2)$$

The control target of the platoon model is that the intervehicle spacing errors and the relative speed of any adjacent vehicles tend to be zero.

2.2. Car-Following Rules. String stability should be guaranteed when vehicles travel in a fleet. Because the spacing error is not expected to be zero when the preceding vehicle accelerates or decelerates, it is necessary to describe how the spacing error is propagated along the platoon when using the same spacing policy. The stable driving of a platoon needs to ensure that the spacing error does not amplify along the platoon [27]. Therefore, the desired characteristic of the transmission attenuation of spacing errors can be described as

$$\|\delta_i\|_{\infty} \leq \|\delta_{i-1}\|_{\infty}. \quad (3)$$

Let $G(S)$ be the transfer function related to the spacing errors of consecutive vehicles in a fleet, we obtain

$$G_i(s) = \frac{\delta_i(s)}{\delta_{i-1}(s)}. \quad (4)$$

When

$$\|G(s)\|_{\infty} \leq 1, \quad (5)$$

we obtain

$$\|\delta_i\|_2 \leq \|\delta_{i-1}\|_2. \quad (6)$$

Equation (6) ensures that the energy of the output error is less than that of the input error. However, it is difficult for this condition to fully meet the desired characteristics of the transmission attenuation of spacing errors.

The ∞ -norm of $G(S)$ and the 1-norm of $g(t)$ can make the output value of the system correlate with the input value of the system:

$$\|g\|_1 = \sup_{x \in L_{\infty}} \frac{\|\delta_i\|_{\infty}}{\|\delta_{i-1}\|_{\infty}}. \quad (7)$$

To satisfy equation (3), the formula below needs to be satisfied.

$$\|g\|_1 \leq 1. \quad (8)$$

According to the theory of linear systems, we obtain

$$|G(0)| \leq \|G(j\omega)\|_{\infty} \leq \|g\|_1. \quad (9)$$

When $g(t) > 0$, we get

$$|G(0)| = \left| \int_0^{\infty} g(t) dt \right| \leq \int_0^{\infty} g(t) dt = \|g\|_1. \quad (10)$$

Therefore, equation (8) that satisfies the desired characteristics of the transmission attenuation of spacing errors can be replaced by the following two conditions:

$$\begin{cases} \|G(s)\|_{\infty} \leq 1, \\ g(t) > 0, \quad \forall t \geq 0, \end{cases} \quad (11)$$

where $G(S)$ is the transfer function of the spacing error of consecutive vehicles in the fleet and $g(t)$ is the impulse response function.

2.3. Spacing Policy. The spacing policy for longitudinal control of vehicular platoons is mainly divided into two types: constant spacing [28] and variable spacing [29]. When adopting the constant spacing, the distance between two adjacent vehicles in the platoon does not change with driving conditions, which can tremendously increase the traffic density. However, adopting this spacing policy requires more complicated communication methods, and in the case of external interference or large communication delay, this spacing policy will seriously affect the stability and safety of the platoon. Therefore, in order to ensure the string stability of the mixed platoon, we adopt the constant time-headway (CTH) policy.

For the CTH policy, the desired spacing between two consecutive vehicles varies linearly with speed:

safety. Therefore, a precise and suitable risk index plays an important role in car-following processes.

4.1. Risk Quantification for HDVs. Driving behavior is the result of the driver's judgment based on his/her psychological expectations under the stimulation of external environmental information. There is a psychological field during the HDV car-following processes [30]. When the external traffic environment changes, it will exert the forces on the psychological field, thereby adjusting the speed and direction of the vehicle. To describe the car-following behaviors of HDVs, in this manuscript, we propose a quantitative index, virtual total energy, based on the MSD car-following model and psychological field theory. We divide the drivers' psychological status into three zones, which are shown in Figure 3. When the virtual total energy varies with car-following errors, drivers' psychological status will be in different zones. Correspondingly, they will perform different vehicle maneuvers, as shown in Figure 4. For example, when the platoon is disturbed during driving, such as the sudden deceleration of the leading vehicle, this will cause the spacing errors Δx and speed errors Δv of the following vehicles to suddenly increase. Correspondingly, in the MSD system, the energy generated by springs and dampers will be greater, which will produce a sense of depression for the driver, forcing him/her to perform braking until his/her psychological depression has disappeared. When the leading vehicle accelerates, the driver's psychology depression is fully released, and the following vehicle will also accelerate until it travels at the desired speed. Ideally, when the following vehicle travels exactly as the preceding vehicle, the driver will maintain the vehicle's speed. Therefore, it is appropriate for the virtual total energy to quantify the level of danger during the car-following processes.

In the MSD model, when the distance between two adjacent cars is less or greater than the desired distance, the spring will be compressed or stretched. According to Hooke's law, the force generated by a spring is proportional to its deformation variable Δx . From the relationship of work and energy, we know that when the spacing error is Δx , the energy generated by the spring is

$$V_{t,i} = \int_{\Delta x} kx \, dx. \quad (22)$$

When the speed of the following car is less than or greater than that of the leading car, the energy consumption of the damper is

$$D_{t,i} = \int_{\Delta v} cv \, dv. \quad (23)$$

Therefore, in the MSD system, when the platoon is disturbed by external environment, the virtual energy generated by the i^{th} vehicle can be expressed as

$$E_{t,i} = V_{t,i} + D_{t,i}. \quad (24)$$

At the same time, the virtual total energy of the entire platoon can be expressed as

$$E_{T,t} = \sum V_{t,i} + \sum D_{t,i}. \quad (25)$$

4.2. Risk Quantification for CAVs. CAVs can quickly obtain the driving information (speed and position) from other vehicles within the communication range. Therefore, the CAVs can detect abnormal driving behaviors in the platoon earlier and take actions in advance. Although there is no psychological field during the car-following process of CAVs, in the MSD system, they still use the spacing errors and speed errors of adjacent vehicles as the control reference index. Therefore, in this manuscript, we consider the virtual total energy as a proper index to reflect the risk of a platoon based on the MSD car-following model:

$$E_{T,a} = \sum V_{a,i} + \sum D_{a,i}. \quad (26)$$

5. Parameter Optimization Based on Minimum Total Energy

In the mixed MSD system, k_a and c_a represent the control gains of relative position and relative speed between adjacent CAVs; k_t and c_t represent the control gains of relative position and relative speed between CAV and HDV, respectively. For the vehicle in the mixed platoon, the virtual energy generated by the interference from the external environment can be expressed as

$$E_{T,i} = \frac{1}{2} \omega(k) \cdot \Delta x_i^2 + \frac{1}{2} \omega(c) \cdot \Delta v_i^2, \quad (27)$$

where $\omega(k) = \begin{cases} k_a, & k \text{ between CAVs} \\ k_t, & k \text{ between CAV and HDV} \end{cases}$ and $\omega(c) = \begin{cases} c_a, & c \text{ between CAVs} \\ c_t, & c \text{ between CAV and HDV} \end{cases}$.

It can be seen from equation (27) that the values of k_a (k_t) and c_a (c_t) will directly affect the energy accumulation of CAVs and HDVs during the car-following processes, so it is necessary to optimize their values to get a better control effect of the mixed platoon.

The magnitude of E represents the virtual energy generated by the corresponding car-following errors. When a vehicle collides, we assume that $E = \infty$, which means that the vehicle's car-following errors reach the maximum. In the car-following processes without an accident, as E gradually becomes smaller, the vehicle's car-following errors also become smaller. When $E = 0$, it means that the vehicle is driving at the desired speed and intervehicle spacing completely, and the driving status is in absolute safety. When the leading vehicle performs emergency braking, the CAVs in the platoon can obtain the driving information of the leading vehicle and the preceding vehicle in real time through V2X technology and immediately apply the brakes. At this point, the virtual energy generated by the car-following errors from CAVs is small. However, if it is followed by a HDV, the driver needs a certain reaction time to take

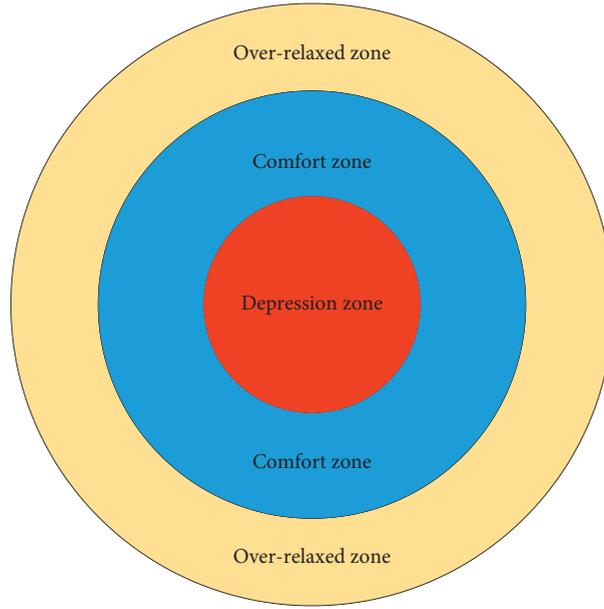


FIGURE 3: Three zones of drivers' psychological status.

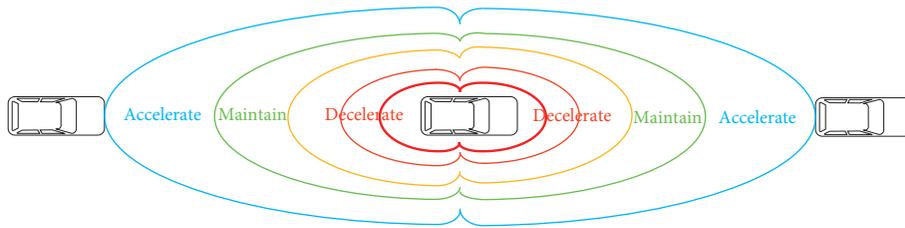


FIGURE 4: Vehicle maneuvers based on drivers' psychological status.

corresponding measures. Obviously, the virtual energy generated by the pair of HDV and CAV will be relatively large, which will cause the vehicles to be unstable or even have a collision. The ideal situation is that when the CAVs brake, they will not only consider their own driving conditions but also reserve a certain braking distance for the HDVs that follow them. Although this will increase the CAVs' accumulated energy, the increased braking distance can greatly improve the driving safety for the following HDVs, which also reduces the energy accumulation. Overall, the total energy of the platoon will be reduced because collisions are avoided. Therefore, for the mixed vehicular platoon based on the MSD system, we propose taking the minimum total energy as the optimization objective of the car-following model:

$$\min \sum \frac{1}{2} \omega(k) \cdot \Delta x_i^2 + \sum \frac{1}{2} \omega(c) \cdot \Delta v_i^2. \quad (28)$$

Based on the assumptions of Section 3, the mass m_C (m_H) and the maximum deceleration d_{\max} of each vehicle in the platoon are known. The platoon when only considering the spring is shown in Figure 5, and its dynamic equation is

$$m_C d_{\max} = k_{\max} \Delta x_{\max}. \quad (29)$$

Therefore,

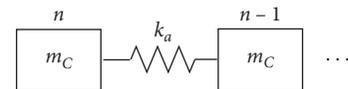


FIGURE 5: MS car-following model.

$$k_{\max} = \frac{m_C d_{\max}}{\Delta x_{\max}}. \quad (30)$$

Similarly, when the platoon only considers the effect of the damper, we obtain

$$c_{\max} = \frac{m_C d_{\max}}{\Delta v_{\max}}. \quad (31)$$

In addition, for realistic control, vehicles in a mixed platoon need to consider their actual performance and dynamic constraints:

$$\begin{cases} \dot{x}_i = v_i, \\ \dot{v}_i = a_i, \\ m_H a_i = k_t \Delta x_{i-1} + c_t \Delta v_{i-1} - k_a \Delta x_i + c_a \Delta v_i, \end{cases} \quad (32)$$

where a_i is the acceleration of the i^{th} vehicle.

Therefore, the parameter optimization problem based on the minimum total energy can be expressed as

$$\begin{cases}
 \min f(x) = \sum \frac{1}{2} \omega(k) \cdot \Delta x_i^2 + \sum \frac{1}{2} \omega(c) \cdot \Delta v_i^2, \\
 \text{s.t. } \dot{x}_i = v_i, \\
 \dot{v}_i = a_i, \\
 m_H a_i = k_t \Delta x_{i-1} + c_t \Delta v_{i-1} - k_a \Delta x_i + c_a \Delta v_i, \\
 a_{i,\min} \leq a_i \leq a_{i,\max}, \quad i = 1, 2, \dots, n, \\
 0 < k_a < k_{a,\max}, \\
 0 < c_a < c_{a,\max}, \\
 0 < k_t < k_{t,\max}, \\
 0 < c_t < c_{t,\max}, \\
 k_t - k_a < 0, \\
 c_t - c_a < 0.
 \end{cases} \quad (33)$$

For the above-mentioned multidimensional constrained nonlinear programming problem, we solve it in Matlab. As shown in Figure 6, the red point represents the optimal solution of the spring stiffness (k) and damping coefficient (c).

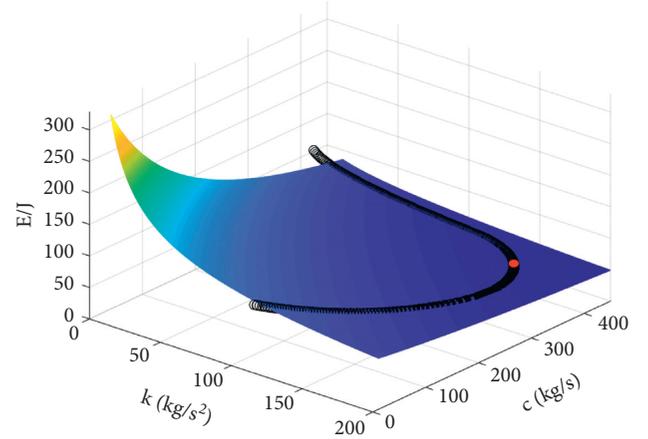


FIGURE 6: Parameter optimization based on minimum total energy.



FIGURE 7: Driver-in-the-loop test platform.

6. Driver-in-the-Loop Test and Results Analysis

6.1. Establishment of Driver-in-the-Loop Platform and Test Scenarios. In view of the high cost and high risk of actual vehicle tests, driving simulators are widely used for research on traffic safety and driving behaviors [31]. The driver-in-the-loop test platform built in this manuscript is shown in Figure 7. It mainly includes a Logitech G29 vehicle controller (steering wheel, pedal, and gear lever) and two sorts of simulation software (PreScan and Matlab/Simulink). PreScan provides a rich set of scene elements to restore real-life driving conditions to a high degree, and its built-in vehicle dynamics model supports Logitech G29 to control the vehicle in real time. In addition, we build the MSD car-following model in Matlab/Simulink, and the joint simulation is performed with PreScan to verify the validity of the proposed MSD car-following model for mixed platoons.

As shown in Figure 8, the mixed vehicular platoon involved in the driver-in-the-loop test consists of 3 CAVs and 2 HDVs. The first and fourth vehicles are HDVs, and the rest are CAVs. The first HDV and the fourth HDV are controlled by drivers through Logitech G29. At the same time, the initial speed of each vehicle in the vehicular platoon is set to 30 m/s plus $\pm 5\%$, and it is made to fluctuate randomly. The

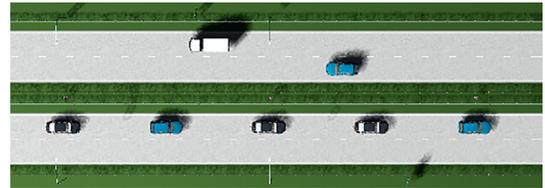


FIGURE 8: Test scenario for the mixed platoon.

distance between two consecutive vehicles varies according to different velocity. At time $t=0$, human factors cause the leading vehicle to perform emergency braking.

6.2. Simulation Parameters. To make the simulation close to the real scene, we assume that the mass and length of each vehicle in the mixed platoon are different. During the car-following processes, the deceleration of the vehicle is limited by the vehicle's motion characteristics and road environment. In this manuscript, all the vehicles travel straight on a dry and flat road. Therefore, we assume that the peak rolling adhesion coefficient is 0.85, and the maximum deceleration of the vehicle is detailed in Table 1, where the other vehicle simulation parameters are also expanded. To improve the

TABLE 1: Vehicle simulation parameters.

Vehicle number	Mass (kg)	Length (m)	Maximum deceleration (m/s ²)	Initial speed (m/s)	Initial position (m)
1	1570	5.48	-7.9	30.0	147.52
2	1240	4.84	-8.3	29.2	110.04
3	1350	5.12	-8.1	30.7	74
4	1680	5.68	-7.7	28.5	36.18
5	1430	5.35	-8.0	30.3	0

traffic capacity, we set the minimum safety distance to 2 m. In addition, the values of k (k_t) and c (c_t) will directly affect the car-following behaviors. Thus, by adjusting the values of k (k_t) and c (c_t) in the MSD car-following model, we can simulate the driving characteristics of different drivers. The specific parameters in this manuscript are shown in Table 2.

After setting the parameters, the car-following test can be completed through the cyclic process shown in Figure 9.

TABLE 2: MSD system parameters.

Vehicle number	Spring stiffness (kg/s ²)	Damping coefficient (kg/s)
1-2	96	196
2-3	83	173
3-4	176	382
4-5	81	169

6.3. Results Analysis. The optimal parameters in the previous section are used to verify the validity of the MSD model for a mixed platoon in the driver-in-the-loop test platform, and the test results are shown in Figure 10. It can be seen from Figure 10(a) when the leading vehicle performs emergency braking, each following vehicles take corresponding measures to brake. In particular, the CAV in the middle position (the third vehicle) maintains the same deceleration as the preceding vehicle in the early stage of braking. However, in the later stage of braking (the red circles in Figure 10(a)), the deceleration of the third vehicle changes sharply under the premise of ensuring safe driving, which reserves enough time for the following HDV to brake. At the same time, it can be seen intuitively from Figure 10(b) that there are no collisions between all vehicles in the mixed platoon and the intervehicle spacing between the three CAVs and their preceding vehicle is always within a reasonable error range. When the CAVs stop, the minimum distance between them is 2.05 m, which is slightly greater than the minimum safety distance ($s_0 = 2$ m). However, the minimum distance between the fourth HDV and the CAV in the middle position is 3.39 m. The above results indicate that each CAV in the mixed platoon can make full use of the braking distance and adjust the gap between each vehicle optimally, which can provide the driver of HDV with sufficient reaction time and braking distance to effectively avoid rear-end collisions.

According to the analysis of the above test results, it can be considered that the proposed MSD model can capture the car-following behaviors of CAVs with high accuracy. However, the MSD car-following model for HDVs needs further analysis. Therefore, we compare the MSD model with the traditional mass-spring (MS) model [19] using the driver-in-the-loop test platform. We establish the test scenarios that are the same as that in Figure 8, and all the initial conditions of the vehicles are also the same. The results are shown in Figure 11.

As shown in Figure 11(a), in the early stage of braking (0~6.2 s), the maximum speed error between the MSD model and the driver is 0.30 m/s, and the variance is $0.135 \text{ m}^2/\text{s}^2$; the maximum speed error between the MS

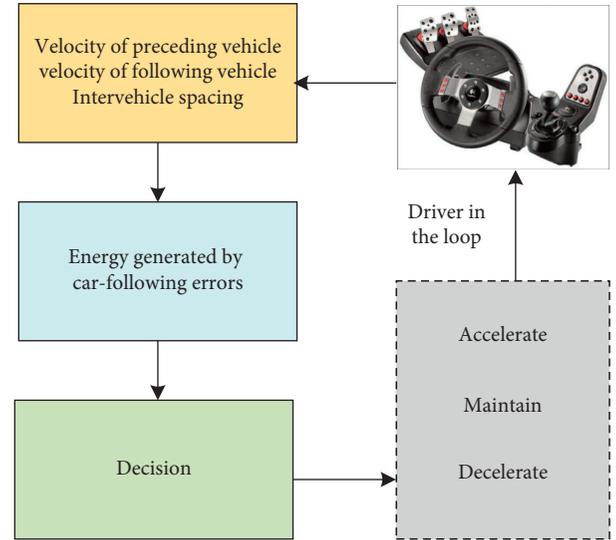


FIGURE 9: Test process of the mixed platoon.

model and the driver is 0.77 m/s, and the variance is $0.227 \text{ m}^2/\text{s}^2$. In the later stage of braking (6.2~15 s), the maximum speed error between the MSD model and the driver is 0.27 m/s, and the variance is $0.187 \text{ m}^2/\text{s}^2$. However, the maximum speed error between the MS model and the driver is 1.02 m/s with a variance of $0.673 \text{ m}^2/\text{s}^2$. Overall, both car-following models can accurately describe the driver's driving behavior during the braking process, but the MSD car-following model is more accurate than the MS car-following model. This is because the MS model only considers the spacing errors of the platoon. Similarly, it can be intuitively seen from Figure 11(b) that the spacing errors of the MSD car-following model are smaller than that of the MS car-following model, so the MSD car-following model can accurately describe the drivers' driving behaviors.

In the car-following processes, the virtual energy caused by the car-following errors in the mixed platoon is shown in Figure 12. Figure 12(a) shows the virtual total energy generated by the errors of spacing and speed of all

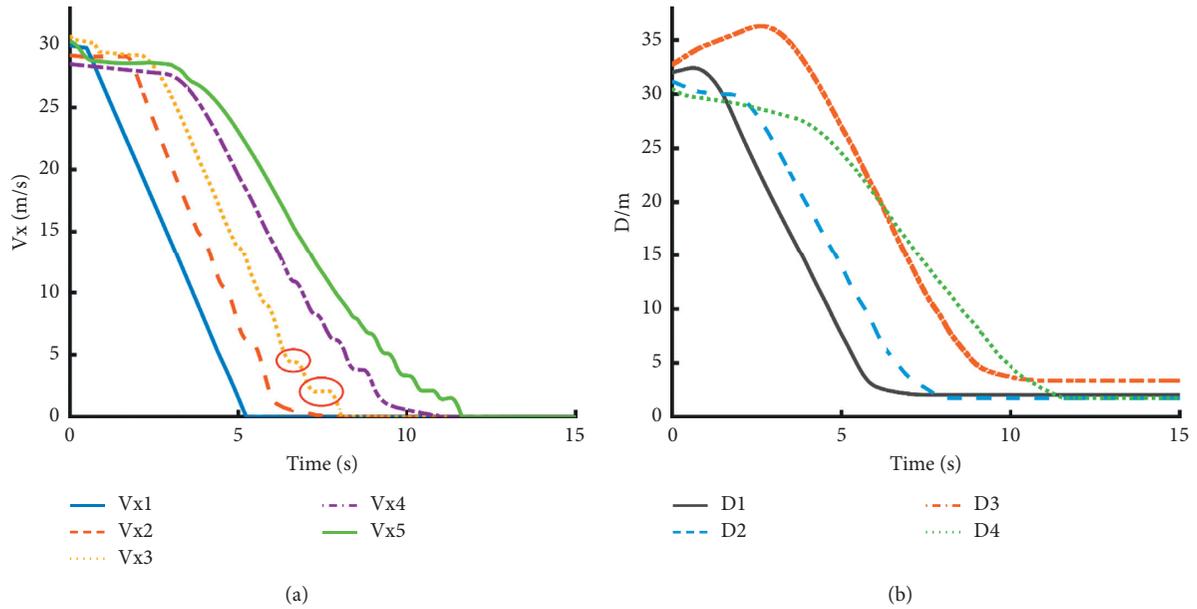


FIGURE 10: Test results of the mixed platoon. (a) Longitudinal velocity. (b) Intervehicle spacing.

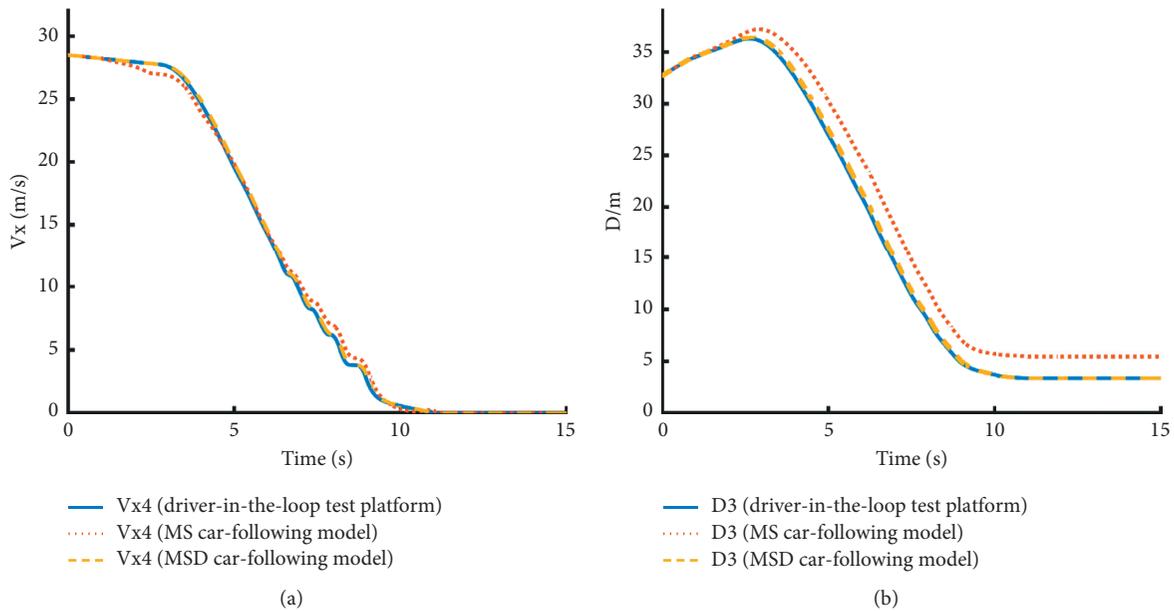


FIGURE 11: Results of comparison test. (a) Longitudinal velocity. (b) Intervehicle spacing.

vehicles in the platoon. Figure 12(b) and Figure 12(c) show the energy generated by the spacing errors and speed errors between adjacent vehicles, respectively. It can be seen from these figures that 67.2% of the energy in the mixed platoon is caused by the HDV (the fourth vehicle), and the energy of spacing error and the energy of speed error have not achieved peak simultaneously. The peak energy of speed error (7878 J) is more than triple that of spacing error (2477 J). Furthermore, in the early stage of

the emergency braking, the spacing error is the dominant factor influencing the car-following behaviors, but in the later stage of the emergency braking, the speed error becomes the decisive factor of the car-following behaviors. Overall, CAVs possess good car-following characteristics, and the errors of spacing and speed between them are small. However, errors of spacing and speed between HDV and CAV are relatively large during the emergency braking processes.

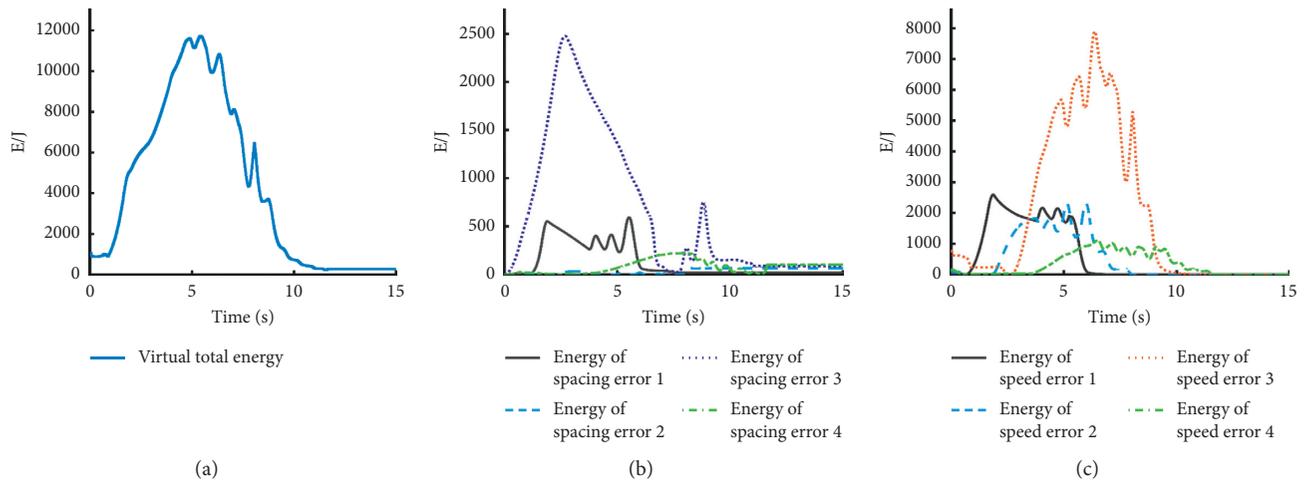


FIGURE 12: Energy accumulation of the mixed platoon. (a) Total energy accumulation. (b) Energy generated by spacing errors. (c) Energy generated by speed errors.

7. Conclusions

In this paper, from the perspective of a mechanical system, a novel car-following model for mixed platoons with CAVs and HDVs was established based on the mass-spring-damper theory. Both relative speed and intervehicle spacing were taken into account in this MSD car-following model, which can effectively capture the car-following behaviors of CAVs and HDVs. Furthermore, the driving characteristics of different vehicles can be described by adjusting the magnitude of the spring stiffness and damping coefficient. At the same time, a quantitative index was proposed in this paper based on the psychological field theory and MSD model, which can indicate the virtual total energy caused by car-following errors of a mixed platoon. Therefore, the magnitude of the energy can be used to quantitatively reflect the danger level of vehicles in the car-following processes. The driver-in-the-loop test was conducted to verify the validity of the proposed MSD car-following model, and the key parameters in the MSD system were determined by the optimal solution based on minimum total energy. Compared with the traditional MS car-following model, the proposed MSD model possesses higher accuracy and it can better describe the car-following behaviors of CAVs and HDVs. Meanwhile, the virtual total energy is an acceptable index to quantify the risk of a mixed platoon. Most of the energy generated by the car-following errors of the mixed platoon is caused by the HDV. In the early stage of emergency braking, the spacing error is the dominant factor of the car-following behaviors and the decisive factor of those in the later stage of emergency braking is the speed error. An obvious conclusion is that the proposed MSD car-following model has great potential to enhance the overall safety of the mixed traffic flow with CAVs and HDVs.

While the MSD car-following model can effectively describe the longitudinal behavioral interactions of a mixed platoon, some future research is still needed. First, this research only conducted driver-in-the-loop tests on CAVs and HDVs with the emergency braking maneuvers. In the

subsequent research, more complicated and real-life driving conditions will be fully considered, and the effectiveness of the MSD car-following model will be further verified. Second, an expansion of the lateral driving behaviors based on the MSD theory will be explored in the future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

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

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