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Cooperative Multi-Objective Control of Heterogeneous Vehicle Platoons on Highway with Varying Slopes

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Abstract: Stability, vehicle safety, energy saving, and passenger comfort are the major objectives of vehicle platooning control. These objectives are coupled, interrelated, and even conflicting, so integrated optimization of multiple objectives is quite challenging. Particularly for heterogeneous platoons, the difficulties are intensified for the differences in vehicle dynamics. In this paper, the concept of symmetry is utilized in the platooning control, that is, the design method of each vehicle's controller is the same. For each controller, it is to solve the optimal solution of multi-objective collaborative optimization. The concept of asymmetry is meanwhile embodied in the parameter setting of each controller, for the vehicle heterogeneity. The contents of this study are as follows. First, a mathematical model is established, in which the differences in vehicle dynamic characteristics of heterogeneous platoon, road slope, and aerodynamics are all taken into account. Then, based on distributed nonlinear model predictive control (DNMPC) method, multi-objective control strategies are proposed for the leader and followers, cooperatively. Furthermore, a weight coefficient optimization method is presented, to further improve the platoon's multi-objective synthesis performance. Finally, comparative experiments are carried out. Results demonstrate that, compared with the classic cruise control method of vehicle platoons, the proposed approach can reduce energy consumption by more than 5% and improve tracking performance on the premise of passenger comfort. Real-road experiments verify that the proposed control system can function effectively and satisfy the computational requirements in real applications.

Keywords: heterogeneous vehicle platoon; multi-objective control; nonlinear model predictive control; distributed control; energy saving

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1. Introduction

Currently, there is a widespread concern over vehicle platoon studies due to their considerable potential to enhance road safety, reduce energy consumption and improve traffic efficiency. Early research mainly focused on homogenous platoons. In recent years, more and more studies on heterogeneous platoons have been carried out. Stability, vehicle safety, energy saving, and passenger comfort are the major objectives in the control of autonomous vehicles. Previous studies on heterogeneous platoons have probably focused on one or two objectives, especially stability control. It is of great significance to study the multi-objective control method of heterogeneous platoons, taking all the four objectives into account.

The study on vehicle platoons can trace back to the California PATH project in the 1980s, which proposed the concept of "Platoon" for the first time [1,2]. Since then, vehicle platooning control has been a topic of wide concern. The existing studies on platooning control could be classified according to different control objectives, as shown in Table 1.

The early studies mainly focused on tracking control and stability control [3–10], which are the basis of vehicle platoons. Tracking control is usually achieved by the cruise control system. A Swedish scholar, Alam, proposed a control structure for the truck platoon, in which the leader was controlled by cruise control and the followers were controlled by adaptive cruise control (ACC) [11]. With the development of vehicle-to-vehicle (V2V) communication technology, the cooperative adaptive cruise control (CACC) system gradually attracted more and more attention [12]. Chiedu, N.M. and Keyvan, H.Z. studied a stability analysis of CACC-based platoons [13]. Rakkesh et al. studied a homogenous platoon composed of eight vehicles to compare CACC and ACC systems, and it was proven that the CACC system had better vehicle tracking and energy saving performance [14]. Zegers et al. designed a multi-layer control architecture based on CACC, in order to achieve the stability of and the expected spacing between vehicles of the platoon [15].

Most of the above research was conducted on homogenous platoons. The studies on heterogeneous platoons are more meaningful in practical applications, and, in the meanwhile, more difficult due to the significant differences in dynamic characteristics between vehicles [16,17]. In recent years, many scholars have been committed to studies on heterogeneous platoons, mainly on stability control. Reference[18] analyzed the stability control of a heterogeneous platoon with switched interaction topology, time-varying communication delay, and lag of actuators. Delft University of Technology proposed a novel CACC method for heterogeneous platoons, which effectively achieved stability control [19]. Scholars at the University of Manchester proposed a two-layer distributed control scheme to maintain the stability of a heterogeneous vehicle platoon moving with a constant spacing policy assuming constant velocity of the leading vehicle [20]. In reference [21], stability control for a heterogeneous vehicle platoon was studied, subject to external bounded unknown acceleration disturbances. Reference [22] presented an integrated platoon control framework for heterogeneous vehicles on curved roads with varying slopes and wireless communication delays, in order to guarantee that the perturbations did not grow unbounded as they propagated through the platoon. Zheng et al. at Tsinghua University introduced a distributed model predictive control algorithm for heterogeneous vehicle platoons, which could guarantee internal stability for any unidirectional topology [23]. In 2019, Li et al. further studied the distributed platoon control with more generic topologies [24]. All of these studies aim at the stability control of heterogeneous platoons.

In addition to stability control, studies on energy-saving control of platoons have attracted much attention from scholars. The existing research on energy-saving control of platoons can be categorized into three approaches, shown as follows:

(1) Energy-saving control based on decreasing the air resistance of vehicles: References [25,26] analyzed the aerodynamics of vehicle platoons, and studies in reference [26] have shown that vehicles in different positions of a platoon faced different air resistance. Swedish scholars have designed a small distance between vehicles of a platoon in order to increase the fuel efficiency [27]. Chalmers University of Technology utilized a stochastic optimization method to optimize the speed curve of the leading vehicle, and this method was proven to be more energy efficient than cruise control [28].

(2) Energy-saving control by avoiding unnecessary rapid accelerations or decelerations of platoons based on road information and predicted information of the surrounding vehicles [5]: Turri et al. at the Royal Swedish Institute of Technology proposed a two-layer control architecture for heavy-duty truck platoons [29]. The upper layer obtained and predicted the road geometry information, and utilized a dynamic programming method to calculate the optimal speed curve of platoons. The lower layer achieved vehicle safety and energy saving control based on the MPC method. Assad Alam et al. studied the influence of different road slopes on the fuel consumption of heavy-duty truck platoons, and proposed a method to calculate the optimal energy-saving speed curve by predicting the information of the road ahead [30]. Zhang et al. at Tsinghua University designed an energy management strategy based on predicting the behavior of the preceding vehicles [31].

(3) Energy-saving control based on reducing frequent gear shifts: Valerio Turri et al. discussed a control architecture that could calculate the optimal sequence of gear shifts for a given reference speed profile, and this could realize energy saving and smooth tracking [32].

In the above studies, the majority focused on one single performance factor as the experimental objective, and only a few concerned two objectives, mainly for homogeneous platoons, such as refs. [5,6,11,14]. Recently, some scholars have gradually become concerned about the multi-objective control of heterogeneous platoons. Zhai et al. [33] proposed a switched control strategy of heterogeneous vehicle platoons for multiple objectives with state constraints. In this study, although multiple objectives were taken into account, only fuel economy was designed as an objective function, while vehicle safety and passenger comfort were designed as state constraints. In other words, this method could optimize the single performance of energy saving, and did not actually achieve the integrated optimization of energy saving, safety, and passenger comfort.

Table 1. Classification of existing vehicle platooning control studies.

Tracking/Safety Performance	Stability Performace	Energy-Saving Performance	Comfort Performance
[3–7,11–14,16,33]	[8–10,15,17–24]	[5,11,14,17,25–32,33]	[6,33]

In summary, fruitful results have been achieved on the stability control or energy-saving control of vehicle platoons. However, the existing studies mainly focus on one or two objectives, and mostly for homogeneous platoons. There still lack systematic studies on multi-objective control of heterogeneous platoons. The major challenge is to achieve the integrated optimization of the four major objectives, for the reason that these objectives are coupled, interrelated, and sometimes even conflicting and contradictory. Furthermore, the vehicle dynamics differences for heterogeneous platoons exacerbate the difficulty. The motivation of this work is to solve this problem. The main work and contributions are as follows:

(1) **A two-layer architecture of the heterogeneous platoon control system is presented**, consisting of a control layer and a dynamic layer, with a distributed controller for each vehicle. This hierarchical and distributed structure is especially suitable for heterogeneous platoon. For dynamic layer, a nonlinear dynamic model of a heterogeneous platoon is presented, characterizing the differences in dynamic properties between vehicles and the influence of the road slope and wind resistance. For the control layer, a wealth of information is utilized for multi-objective solving, including not only the current states of the vehicles, but also their predicted states over a period of time, as well as the expected control signals.

(2) **A cooperative multi-objective control strategy of a heterogeneous platoon is proposed, based on distributed nonlinear model predictive control (DNMPC) method.** Multi-objective DNMPC controllers are designed for the leading vehicle and the following vehicles, cooperatively. For each controller, objective function integrates multiple sub-objective functions, each of which depicts one targeted performance. With this method, the optimization of multiple targets of heterogeneous platoons can be achieved.

(3) **A weight coefficient optimization method based on a non-dominated sorting genetic algorithm (NSGA-II) is presented**, to obtain the optimal weight coefficient set of multiple targets. Instead of the common empirical method in the existing studies, this proposed method is able to achieve coordinated adjustment between multiple targets, which can effectively improve the multi-objective collaborative optimization capability of the heterogeneous platoons.

The remainder of this paper is organized as follows. Section 2 describes the multi-objective control system architecture, and demonstrates the dynamic model of the heterogeneous platoon. In section 3, the cooperative multi-objective control strategy based on the DNMPC method is presented. The stability analysis based on the Lyapunov theory is introduced as well. Section 4 elaborates on the NSGA-II-based weight coefficient optimization method. Section 5 describes the simulation experiments and real-road tests. Section 6 presents the main conclusions of this investigation.

2. Cooperative Multi-Objective Control System of a Heterogeneous Platoon

2.1. Architecture of the Multi-Objective Control System of a Heterogeneous Platoon

The architecture of the multi-objective control system of a heterogeneous platoon is shown in Figure 1, where α represents the road slope, and $u_i^*(:|t)$ (i = 1,…, n) is the optimal control variable of vehicle i, calculated by its controller at time t. $u_i^*(:|t)$ is a sequence, composed of N_P control variables during a predicted time domain [t, $t + N_P \Delta t$], and there are N_P time steps in one predicted time domain. $u_i^*(1|t)$ is the optimal control variable for the present moment, and y_i refers to the state information of vehicle i, specifically including vehicle position, speed, and the torque.

As shown in Figure 1, the architecture is a two-layer one. The control layer is composed of the DNMPC controllers of each vehicle. In this study, the concept of symmetry is utilized in the platooning control, that is, the design method of each vehicle's controller is the same. Each controller obtains road information, and sends the optimal control signal to the dynamic layer, from which the state information of each vehicle can be acquired. Dynamic layer is the dynamic model of the heterogeneous platoon.

The proposed architecture and control method in this paper are applicable for various types of communication topologies. In this paper, a predecessor-following leader (PFL) type of communication topology is selected for illustration, which has been reflected by the dashed lines in Figure 1.

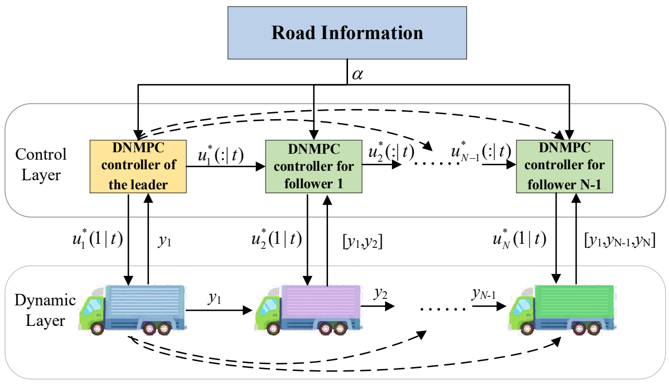


Figure 1. Architecture of the multi-objective control system of a heterogeneous platoon.

The architecture possesses the following advantages:

(1) With a distributed control method for the control layer, each controller is designed with full consideration of the differences in dynamic characteristics between the vehicles. This makes it possible to achieve the best overall performance of the heterogeneous platoon. Moreover, compared with centralized control, it better computational real-time performance, which is more conducive to practical application.

(2) Rich information is supplied to the controller for the calculation of the optimal control variables. The predicted information is fully utilized, which can effectively improve the stability and energy-saving performance of the platoon. As shown in Figure 1, for vehicle i, its controller could obtain the vehicle's current state y_i, control signals $u_i^*(:|t)$, the leading vehicle's state and control signals, y_1 and $u_1^*(:|t)$, and the neighboring vehicles' state and control signals, y_{i-1} and $u_{i-1}^*(:|t)$. It is important to note that these signals

include not only the current signal, but also the expected one during a predicted time domain.

(3) Based on the vehicle state from dynamic layer, each controller uses a feedforward–feedback control structure, which is beneficial to improve the control effect.

(4) In the dynamic layer, road information and wind resistance are taken into account in the dynamic model of the platoon, which could further improve the platoon's energy-saving performance.

2.2. Dynamic Model of a Heterogeneous Platoon

Force analysis of one vehicle on the ramp is shown in Figure 2, where α represents road slope, F_T for driving force, F_W for air resistance, F_g for slope resistance, and F_f for rolling resistance.

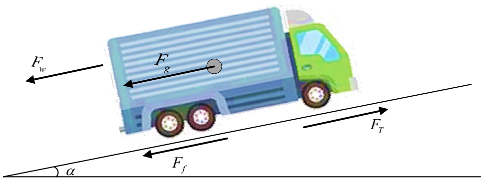


Figure 2. Force analysis of a vehicle on the ramp.

F_T, F_W, F_g, and F_f can be calculated according to Equations (1)–(4), described as follows:

$$F_T = \frac{4 i_0 \eta_m}{r_w} T_q(t) \tag{1}$$

$$F_w = \frac{1}{2} C_d A \rho v^2(t) \tag{2}$$

$$F_f = fmg\cos\alpha \tag{3}$$

$$F_g = mg\sin\alpha \tag{4}$$

where η_m, i_0, r_w and T_q represent the transmission efficiency, transmission ratio, rolling radius of the wheel, and the motor torque, respectively. C_d, A, ρ and v represent the aerodynamic drag coefficient, frontal area, air density, and the vehicle speed. f represents the coefficient of rolling resistance, which of the highway is usually 0.012.

Integrating Equations (1)–(4), the longitudinal dynamics model of one vehicle can be obtained, shown as follows:

$$\begin{aligned} m\dot{v}(t) &= F_T - F_w - F_f - F_g \\ &= \frac{4 i_0 \eta_m}{r_w} T_q(t) - \frac{1}{2} C_d A \rho v^2(t) - fmg\cos\alpha - mg\sin\alpha. \end{aligned} \tag{5}$$

Dynamic characteristics between vehicles of a heterogeneous platoon are different. The dynamic model of a heterogeneous platoon is given as follows:

$$\begin{cases} \dot{S}_i(t) = v_i(t) \\ \dot{v}_i(t) = \dfrac{4 T_{q,i}(t) i_{0,i} \eta_{m,i}}{m_i r_{w,i}} - \dfrac{C_D(d_i) A_i \rho}{2 m_i} v_i(t)^2 - g\sin\alpha - fg\cos\alpha, i \in \mathrm{N} \\ \tau_i \dot{T}_{q,i}(t) + T_{q,i}(t) = u_i(t) \end{cases} \tag{6}$$

where $S_i(t)$, τ_i and $u_i(t)$ represent the position, delay coefficient of driving system, and the expected torque for vehicle i.

In addition to the road slope, the aerodynamics is taken into account when establishing the dynamic model. Reference [34] revealed that a vehicle's air resistance varied with the distance between vehicles. In the existing research, the aerodynamic drag coefficient is usually a constant, which is inconsistent with the aerodynamics characteristics. In this paper, the mathematical formula between aerodynamic drag coefficient and the vehicle spacing is established, given as follows:

$$C_D(d_i) = C_{D,i}^0 (1 - \frac{a_{lsq}}{b_{lsq} + d_i}), \tag{7}$$

where $C_{D,i}^0$ is the nominal air drag coefficient for a single vehicle, a_{lsq} and b_{lsq} are the empirical coefficients [35], and d_i refers to the distance between the ego vehicle and the preceding one. According to Formula (7), the relationship between the air drag coefficient and the spacing is shown in Figure 3. As shown in Figure 3**,** the air drag coefficient is greatly affected by the distance between vehicles, when the distance is within 50 m.

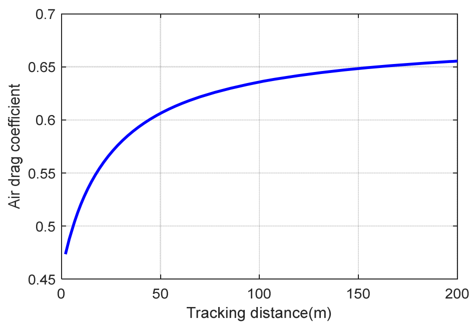


Figure 3. Relationship between air drag coefficient and the spacing.

Equations (6) and (7) form the dynamic model of the heterogeneous platoon, which possesses advantages as follows:

(1) Different properties of each vehicle is presented, such as, η_m, i_0, r_w, and other parameters of each vehicle, can be different.

(2) Road slope and aerodynamics are considered, and the mathematical relationship between air resistance and vehicle spacing is taken into account as well.

3. Cooperative Multi-Objective Control Strategy Based on the DNMPC Method

In this section, a cooperative multi-objective control strategy of heterogeneous platoons based on DNMPC method is presented. DNMPC is the improvement based on MPC, whose important advantage is that multi-objective collaboration can be achieved. Further considering dynamic differences in heterogeneous platoons, the DNMPC method is presented based on MPC. DNMPC controllers are designed for the leader and the followers, respectively and cooperatively.

First, a sub-objective function is designed for each performance. Then, multi-objective function and constraints are established. Finally, for the entire control system of the heterogeneous platoon, stability analysis is conducted based on Lyapunov theory.

3.1. Multi-Objective DNMPC Controller of the Leader

3.1.1. Sub-Objective Function for Energy Saving

The energy-saving objective function $J_1(k|t)$ is expressed as follows:

$$J_1(k|t) = \| W_1 P_1(k|t) \cdot \Delta t \|_2, \tag{8}$$

where W_1 represents the weight coefficient of the energy consumption for the leader, and Δt is a time step. $P_1(k|t)$ represents the motor power, and the energy consumption during the predicted time domain is calculated by accumulating the energy power of the motor for N_p time steps.

The motor power of one vehicle i, that is $P_i(k|t)$, can be calculated separately according to the braking and driving conditions, given by Equation (9). $T_{q,i}$, $r_{w,i}$, $i_{g,i}$, η_d, η_b denote the motor torque, rolling radius of the wheel, transmission ratio, driving efficiency and braking efficiency of the motor for vehicle i.

$$P_i(k|t)=\begin{cases}\dfrac{4T_{q,i}(k|t)v_i(k|t)i_{g,i}}{r_{w,i}\eta_{\mathrm{d}}}, & T_{q,i}(k|t)\geq 0\\ \dfrac{4T_{q,i}(k|t)v_i(k|t)i_{g,i}}{r_{w,i}}\eta_b, & T_{q,i}(k|t)<0\end{cases} \tag{9}$$

3.1.2. Sub-Objective Function for Stability and Passenger Comfort

For the leading vehicle, its speed should keep as constant as possible in order to ensure the platoon stability and passenger comfort. Thus the stability and passenger comfort objective function $J_2(k|t)$ is expressed as follows:

$$J_2(k|t)=\|R_1(u_1^p(k|t)-u_0(v_1^p(k|t)))\|_2, \tag{10}$$

where R_1 represents the weight coefficient, $u_1^p(k|t)$ represents the expected torque of the leading vehicle, and $u_0(v_1^p(k|t))$ is the torque when the vehicle is driving at a constant speed, which is given as Equation (11). In order to improve comfort, the rate of torque change should be kept as low as possible.

$$\begin{aligned}u_0(v_i^p(N_p|t))=&\frac{r_{w,i}}{4i_{0,i}\eta_{m,i}}\Big(\frac{1}{2}C_{D,i}A_i\rho v_i^p(N_p|t)^2\\&+m_i gf\cos\alpha+m_i g\sin\alpha\Big),\quad i=1,\ldots,\mathrm{N}\end{aligned} \tag{11}$$

3.1.3. Multi-Objective Function and Constraints of the Leader

Considering stability, passenger comfort and energy saving targets, the objective function and constraint for the leader's DNMPC controller is designed, shown as follows:

$$\begin{aligned}\min J^1(t)=&\sum_{k=0}^{N_p-1}(J_1(k|t)+J_2(k|t))\\ s.t.\quad & v_{\min}\leq v_1^p(k|t)\leq v_{\max}\\ & T_{\min}\leq u_1^*(k|t)\leq T_{\max}\\ & v_1^p(N_p|t)=v_{eco}\\ & T_{q,1}^p(N_p|t)=u_0(v_1^p(N_p|t))\end{aligned} \tag{12}$$

where $J^1(t)$ represents the comprehensive objective function for the leading vehicle, N_p is the quantity of time steps during a predictive time domain, $v_{\min}$ is the minimum speed for a vehicle on the highway, $v_{\max}$ is the maximum speed, $T_{\min}$ is the minimum torque for the motor, $T_{\max}$ is the maximum torque, v_{eco} is the vehicle's economic speed set by the experience, and $u_1^*(k|t)$ is the optimal control sequence to be solved.

3.2. Multi-Objective DNMPC Controller of the Followers

3.2.1. Sub-Objective Function for Vehicle Tracking Performance

The vehicle tracking performance of the followers represents the driving safety of a platoon, and, meanwhile, has a significant impact on the platoon's stability. In this study, according to the selected PFL communication topology, the tracking performance is described by the tracking error between the ego vehicle and the leader, and then between the ego vehicle and the preceding one.

As shown in Figure 1, y_i refers to the state information of vehicle i. The real state of the ego vehicle i is expressed as Equation (13). The desired state of vehicle i is calculated according to the state of the leader, expressed by Equation (14). The desired state of vehicle i calculated according to the preceding vehicle $i-1$ is expressed as Equation (15).

$$y_i^p = [S_i^p \quad v_i^p \quad T_{q,i}^p]^T \tag{13}$$

$$y_{i,des} = [S_1^a - (i-1)d \quad v_1^a \quad T_{q,1}^a]^T \tag{14}$$

$$y_{i,i-1,des} = [S_{i-1}^a - d \quad v_{i-1}^a \quad T_{q,i-1}^a]^T \tag{15}$$

As shown in Equations (13)–(15), the vehicle state set is composed of the position S, the speed v, and the torque T_q. Superscript p denotes that this state is obtained by in-vehicle sensors, and a denotes that the state is obtained by V2V communication. The state may vary due to the communication delay. d denotes the desired spacing between vehicles. $y_{i,des}$ and $y_{i,i-1,des}$ represent the desired state set of vehicle i calculated according to the leader, and the preceding vehicle, respectively.

Then, the tracking objective function for vehicle i is expressed as Equation (16), where Q_i and G_i are the weight coefficients.

$$\begin{aligned} J_{1,i}(k \mid t) = &\| Q_i(y_{i,des}(k \mid t) - y_i^p(k \mid t)) \|_2 \\ &+ \| G_i(y_{i,i-1,des}(k \mid t) - y_i^p(k \mid t)) \|_2 \end{aligned} \tag{16}$$

3.2.2. Sub-Objective Function for Energy Saving

Similar to the energy-saving sub-objective function for the leader, that for the following vehicle i is expressed as follows:

$$J_{2,i}(k \mid t) = \| W_i P_i(k \mid t) \cdot \Delta t \|_2, \tag{17}$$

where W_i represents the weight coefficient. The calculation method of the vehicle's energy consumption is the same as that of the leader, described as Equation (9).

3.2.3. Sub-Objective Function for Passenger Comfort

Similar to the passenger comfort sub-objective function for the leader, that for the following vehicle i is expressed as follows:

$$J_{3,i}(k \mid t) = \| \mathrm{R}_i(u_i^p(k \mid t) - u_0(v_i^p(k \mid t))) \|_2, \tag{18}$$

where R_i, $u_i^p(k \mid t)$, and $u_0(v_i^p(k \mid t))$ represent the weight coefficient, the expected torque of vehicle i, and the torque when the vehicle is driving at a constant speed, respectively. The calculation of $u_0(v_i^p(k \mid t))$ is the same as that of the leader, expressed as Equation (11).

3.2.4. Sub-Objective Function for Communication Stability

In order to further improve the stability performance of the platoon, the accuracy of information transmission should be ensured. For this, the communication stability sub-objective function is designed, given as follows:

$$J_{4,i}(k \mid t) = \| F_i((y_i^p(k \mid t) - y_i^a(k \mid t))) \|_2, \tag{19}$$

where F_i is the weight coefficient, $y_i^p(k \mid t)$ is the expected state set of vehicle i, and $y_i^a(k \mid t)$ is the state set sent to other vehicles of the platoon by V2V communication.

3.2.5. Multi-Objective Function and Constraints of the Followers

Taking all these targets into consideration at the same time, the objective function and constraints for the follower's DNMPC controller is designed, shown as follows:

$$\begin{aligned}
&\min J^i(t) = \sum_{k=0}^{N_p-1} (J_{1,i}(k|t) + J_{2,i}(k|t) + J_{3,i}(k|t) + J_{4,i}(k|t)) \\
&s.t. \quad v_{\min} \le v_i^p(k|t) \le v_{\max} \\
&\qquad T_{\min} \le u_i^*(k|t) \le T_{\max} \\
&\qquad v_i^p(N_p|t) = v_1^p(N_p|t) \\
&\qquad S_i^p(N_p|t) = S_1^p(N_p|t) - (i-1)d \\
&\qquad T_{q,i}{}^p(N_p|t) = u_0(v_i^p(N_p|t))
\end{aligned} \tag{20}$$

where $J^i(t)$ represents the objective function for the following vehicle i (i = 2,…, n). The terminal constraints are designed to ensure that the vehicle state could be the desired one calculated according to the state of the leader.

3.3. Stability Analysis Based on Lyapunov Theory

The stability of the proposed control system is analyzed based on the Lyapunov theory. The control system can be expressed as follows:

$$x(t) = f(x(t), u^*(t)). \tag{21}$$

Assume that $x = 0$ is a balance point. Based on the framework of Lyapunov theory, the stability is defined as follows:

Definition 1. *For any* $\epsilon > 0$*,there exists* $\delta(\epsilon) > 0$*, satisfying* $\| x(0) \| < \delta(\varepsilon) \Rightarrow \| x(t) \| < \varepsilon, \forall t \ge 0$ *. it is controllable and stable near the initial point* $x = 0$*.*

Definition 2. *If the closed loop system is stable at the balance point* $x = 0$*, and there exists* δ *that satisfies* $\| x(0) \| < \delta \Rightarrow \lim_{t\to\infty} x(t) \to 0$ *, the closed loop system is asymptotically stable nearby the balance point.*

At random moment t, the comprehensive multi-objective function for the vehicle i' s controller is shown as follows:

$$J_\Sigma^*(t) = \sum_{i=1}^{N} J_i^*(x_i(t), u_i^*(\bullet|t)) \tag{22}$$

where i represents the number of the vehicle, and N represents the quantity of the vehicles in the platoon. At the moment t, the cost function for vehicle i is given as follows:

$$\begin{aligned}
J_{i,\Sigma}^*(x(t)) &= L_i(x_i^*(k|t), u_i^*(k|t), x_i^a(k|t), x_j^a(k|t), x_1^a(k|t)) \\
&= \sum_{k=1}^{N_p} \begin{aligned}[t] &\| Q_i(y_{i,des}(k|t) - y_i^p(k|t)) \|_2 \\ &+ \| G_i(y_{i,i-1,des}(k|t) - y_i^p(k|t)) \|_2 \\ &+ \| W_i P_i(k|t) \cdot \Delta t \|_2 + \| \mathrm{R}_i(u_i^p(k|t) - u_0(v_i^p(k|t))) \|_2 \\ &+ \| F_i((y_i^p(k|t) - y_i^a(k|t))) \|_2 \end{aligned}
\end{aligned} \tag{23}$$

At the moment $t + 1$, the value to be optimized is given as follows:

$$\begin{aligned}
&J_{i,\Sigma}^*(t+1) \le \\
&L_i(x_i^*(:|t+1), u_i^*(:|t+1), x_i^a(:|t+1), x_j^a(:|t+1), x_1^a(:|t+1)) \\
&= \sum_{k=0}^{N_p-1} \begin{aligned}[t] &l_i(x_i^*(k|t+1), u_i^*(k|t+1), \\ &x_i^a(k|t+1), x_j^a(k|t+1), x_1^a(k|t+1)) \end{aligned}
\end{aligned} \tag{24}$$

then,

$$
\begin{aligned}
&J_{i,\Sigma}^{*}(t+1)-J_{i,\Sigma}^{*}(t)\leq \\
&-\sum_{k=0}^{N_p-1}L_i(x_i^*(k\,|\,t),u_i^*(k\,|\,t),x_i^a(k\,|\,t),x_j^a(k\,|\,t),x_1^a(k\,|\,t)) \\
&+\sum_{k=1}^{N_p-1}L_i(x_i^*(k\,|\,t),u_i^*(k\,|\,t),x_i^*(k\,|\,t),x_j^*(k\,|\,t),x_1^*(k\,|\,t)) \\
&=-l_i(x_i^*(0\,|\,t),u_i^*(0\,|\,t),x_i^a(1\,|\,t),x_j^a(1\,|\,t),x_1^a(1\,|\,t)) \\
&+\sum_{k=1}^{N_p-1}\{[l_i(x_i^*(k\,|\,t),u_i^*(k\,|\,t),x_i^*(k\,|\,t),x_j^*(k\,|\,t),x_1^*(k\,|\,t)] \\
&-l_i(x_i^*(k\,|\,t),u_i^*(k\,|\,t),x_i^a(k\,|\,t),x_j^a(k\,|\,t),x_1^a(k\,|\,t))\}
\end{aligned}
\tag{25}
$$

Analyzing Equation (25), the formula could be obtained, as follows:

$$
\begin{aligned}
&l_i(x_i^*(k|t),u_i^*(k|t),x_i^*(k|t),x_j^*(k|t),x_1^*(k|t)) \\
&-l_i(x_i^*(k|t),u_i^*(k|t),x_i^a(k|t),x_j^a(k|t),x_1^a(k|t)) \\
&=\sum_{i=1}^{N}\left\{\|G_i(y_j^{\,*}(k|t)-y_i^*(k|t))\|_2-\|G_i(y_j^{\,a}(k|t)-y_i^*(k|t))\|_2\right\} \\
&\quad-\|F_i(y_i^*(k|t)-y_i^a(k|t))\|_2
\end{aligned}
\tag{26}
$$

According to the norm triangle inequality, Equation (26) could be expressed as follows:

$$
\begin{aligned}
&\sum_{i=1}^{N}\left\{\|G_i(y_j^{\,*}(k|t)-y_i^*(k|t))\|_2-\|G_i(y_j^{\,a}(k|t)-y_i^*(k|t))\|_2\right\} \\
&\quad-\|F_i(y_i^*(k|t)-y_i^a(k|t))\|_2 \\
&\leq\sum_{i=1}^{N}\|G_i(y_j^{\,*}(k|t)-y_j^a(k|t))\|_2-\|F_i(y_i^*(k|t)-y_i^a(k|t))\|_2
\end{aligned}
\tag{27}
$$

One single step iteration of each controller is given as follows:

$$
\begin{aligned}
&J_\Sigma^*(x(t+1))-J_\Sigma^*(x(t)) \\
&\leq-\sum_{i=1}^{N}L_i(x_i^*(1|t),u_i^*(0|t),x_i^a(1|t),x_j^a(1|t),x_1^a(1|t))+\sum_{k=1}^{N_p-1}\varepsilon_\Sigma(k)
\end{aligned}
\tag{28}
$$

where,

$$
\varepsilon_\Sigma(k)=\sum_{i=1}^{N}[\sum_{j}\|G_i(y_j(k|t)-y_i^p(k|t))\|_2-\|F_i(y_i^p(k|t)-y_i^a(k|t)\|_2]
\tag{29}
$$

Only if $\sum_{k=1}^{N_p-1}\varepsilon_\Sigma(k)\leq 0$ can the stability of the platoons' control system can be achieved. In the formula, G_i and F_i are the weight coefficients, set by the designers. Therefore, as long as artificially set coefficients satisfy $\varepsilon_\Sigma(k)\leq 0$, the asymptotic stability of the platoon's control system can be guaranteed based on the Lyapunov theory.

4. NSGA-II-Based Weight Coefficient Optimization

The empirical method is commonly utilized to determine the weight coefficient in the existing research. In this study, the NSGA-II-based weight coefficient optimization method is presented, to obtain the optimal weight coefficient set for each following vehicle. This proposed method takes into account the differences in dynamic characteristics between vehicles, and is able to effectively improve the multi-objective integrated performance of the heterogeneous platoon.

For each follower of a heterogeneous platoon, the control block diagram with the NSGA-II-based weight coefficient optimization method is shown in Figure 4.

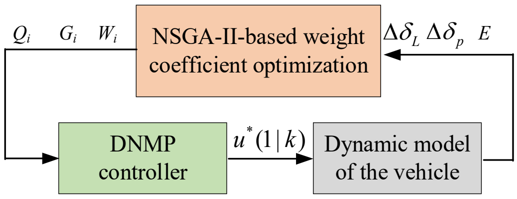


Figure 4. Control block diagram with the NSGA-II-based weight coefficient optimization method.

As shown in Figure 4, the weight coefficient optimization calculation is executed off-line. After one complete control cycle, this optimization calculation is performed. $\Delta\delta_L$ refers to the root mean square of the tracking error between the ego vehicle and the leading vehicle, $\Delta\delta_p$ refers to the root mean square of the tracking error with the preceding vehicle, and E represents the energy consumption of the ego vehicle. Q_i, G_i, and W_i are weight coefficients of the multi-objective function to be optimized. For the weight coefficient optimization module, the objective function is designed as follows:

$$\min L = [\Delta\delta_L(X) \quad \Delta\delta_P(X) \quad E(X)], \tag{30}$$

where X represents the state variable set at any moment through the control cycle.

The optimization solution for the weight coefficients is carried out based on the function shown as Equation (30). The optimization solution process of genetic algorithm (GA) includes selection, crossover and mutation. On the basis of classic GA, the NSGA-II algorithm introduces an elite strategy to further expand the sampling space, which is able to prevent the loss of the optimal solution during the update of the population. The specific solution can be solved simply by using MATLAB, and therefore the solution process will not be described.

5. Simulation and Analysis

In order to verify the effectiveness of the proposed method, a simulation platform is developed, and comparative experiments are carried out. The approach for comparison is the classic cruise control method. Comparison simulation tests have been conducted on the road with designed slope curve, and the actual highway with varying slopes, separately. Moreover, a real-road experiment is conducted to verify the effectiveness and real-time computational performance in real applications.

5.1. Simulation Platform and Simulation Setting

Based on Matlab/Simulink, the dynamic model, the DNMPC controller for each vehicle, the cooperative multi-objective control algorithm, and the off-line weight coefficient optimization algorithm were built for a heterogeneous platoon, which consisted of five trucks. Parameters of the driving road and vehicles were set based on PreScan.

The parameters of the five trucks were designed according to the actual vehicle's parameters of the FAW Jiefang vehicles. Two types of vehicles with different dynamic characteristics were chosen to form the platoon, as shown in Table 2.

Table 2. Dynamic parameters of two types of vehicles.

No.	Mass	Rolling Radius of the Wheel	Frontal Area of the Vehicle
1	3900 kg	0.364 m	2.4 m^2
2	6100 kg	0.497 m	4.8 m^2

For the simulation tests on the road with designed slope curve and tests on the actual highway with varying slopes, the simulation settings are exactly the same. The initial speed of each vehicle is 22 m/s, and the desired speed is 23.5 m/s, which is the average economic-speed on the highway for this platoon. The initial spacing is just the desired one, which is 15 m.

In order to purely verify the effectiveness of the multi-objective control method, in the comparative tests on the two types of roads, the weight coefficients are set as empirical values, according to the traditional way. In this case, the comparison results show completely the differences between these two control methods, without the impact of weight coefficient optimization. Then, the effectiveness of the NSGA-II-based weight coefficient optimization algorithm is verified and comparative test is described in detail in Section 5.2.3.

5.2. Simulation Result and Discussion

5.2.1. Test on the Road with Designed Slope Curve

The comparative simulation test is carried out on the road with designed slope curve for the heterogeneous platoon with five trucks. The road is designed as shown in Figure 5. According to the standard of the highway, the slope range is set as (−0.066, 0.066) rad.

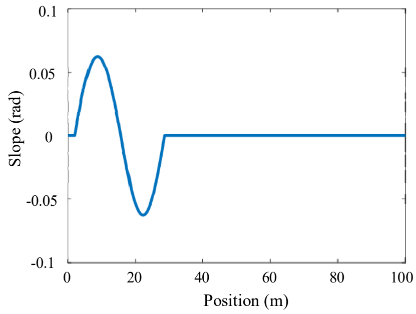


Figure 5. Slope curve of the designed road.

As shown in Table 2, there are two types of vehicles with different masses in the platoon. The performance of the platoon may vary greatly with different mass distributions. In this paper, three platoons with different mass distributions have been tested separately, and their vehicle tracking and energy saving performances have been analyzed, as shown in Table 3.

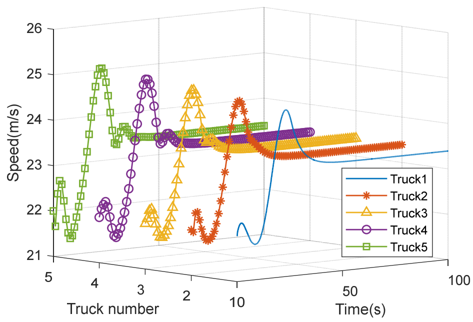
Table 3. Tracking and energy-saving performances of platoons with different mass distributions.

Performances / Mass Distribution	Speed Tracking Error (m/s)	Distance Tracking Error (m)	Energy Consuming (kW·h)
6100, 6100, 6100, 3900, 3900	0.1087	0.3164	2.1364
3900, 3900, 6100, 6100, 6100	0.1136	0.3348	2.0421
6100, 3900, 6100, 3900, 6100	0.1246	0.3442	2.0267
3900, 3900, 3900, 3900, 3900	0.0419	0.0816	1.5269

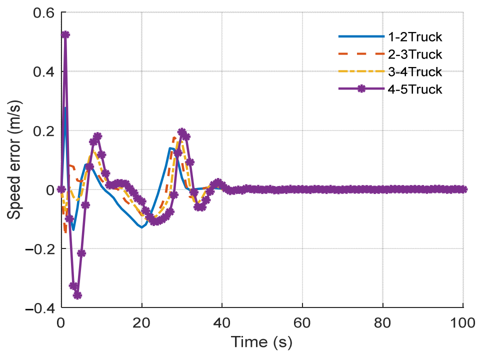
It is obvious from the test results that the control performance of homogeneous platoon is better than that of heterogeneous platoon. It also confirms a consensus that heterogeneity of vehicle dynamics makes platooning control more difficult.

Different types of heterogeneous platoons are tested, as shown in Table 3. Speed tracking error and distance tracking error are typical indicators for tracking/safety performance of platooning control, representing the deviation between actual speed/spacing and the expected one. For platoon 3, in which two types of vehicles are arranged in alternating order, every two adjacent vehicles affect each other, so vehicle tracking performance of this platoon is the worst. With the alternating order, the vehicle with a larger frontal area could withstand wind resistance for the following vehicle, and energy consuming of the following one could be effectively reduced. Therefore, energy saving performance of platoon 3 is the best, as shown in Table 3.

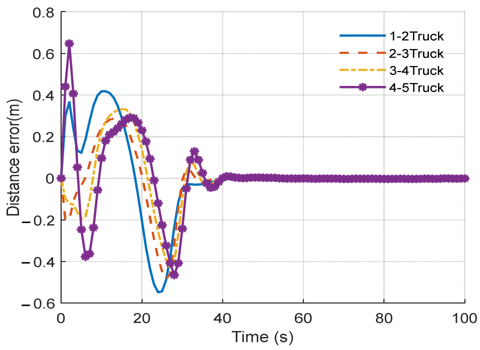
The mass distribution of platoon 1 is the most popular, so platoon 1 is selected in this paper to make the comparative analysis between the proposed DNMPC-based multi-objective control method and the classic cruise control method. For the test on the road with designed slope curve, vehicle speed, speed tracking error, distance tracking error, and energy consumption are shown in Figure 6.



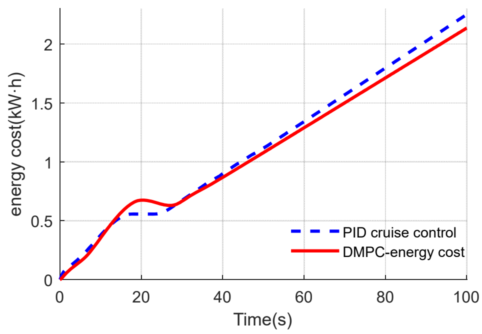
(**a**) Speed curve of each vehicle with the proposed method



(**b**) Speed tracking error with the proposed method



(**c**) Distance tracking error with the proposed method



(**d**) Comparison result of energy consumption

Figure 6. Test results of the heterogeneous platoon driving on the designed road.

According to Figure 6, several points could be drawn, shown as follows.

(1) As shown in Figure 6b, when driving on a sloped road, the proposed DNMPC-based cooperative multi-objective control method can ensure that the tracking error fluctuates in a small range, and the platoon stability could be quickly achieved.

(2) As shown in Figure 6a, the vehicles accelerate a little earlier before going uphill, in order to avoid sudden acceleration when reaching the uphill. During the climbing process, vehicles reduce the speed to ensure sufficient torque. During the downhill process, motors of vehicles do not generate torque, and in the meanwhile, the energy is recovered. As the red line shows in Figure 6d, the energy consumption of the platoon decreases during downhill due to the energy recovery. Thus, it can be seen that the proposed DNMPC-based cooperative multi-objective control method takes into account the impact of road slope on the energy consumption, and calculates an optimized speed curve according to the road slope.

(3) The detailed comparison results of the simulation test on the designed road are shown in Table 4. As can be observed from Table 4, compared with the classic cruise control method, the proposed DNMPC-based multi-objective control method can effectively reduce energy consumption by 5.14%, while maintaining a good vehicle tracking performance.

Table 4. Comparison results of the heterogeneous platoon on the designed road with different control methods.

Control Method / Performances	The Proposed DNMPC-Based Multi-Objective Control Method	The Cruise Control Method
Average speed tracking error (m/s)	0.1087	0.5103
Average distance tracking error (m)	0.3164	0.3157
Total energy consumption (kW·h)	2.1364	2.2523

5.2.2. Test on the Actual Highway with Varying Slopes

In order to further verify the effectiveness of the proposed multi-objective control method, an actual highway is chosen, which is a road section of the highway from Beijing to Tianjin. The slope of the chosen road section is shown as Figure 7, and simulation tests haven been carried out. In order to clearly show the impact of road slope on the test results, a space-time conversion is made and therefore the horizontal axis in Figure 7 is time.

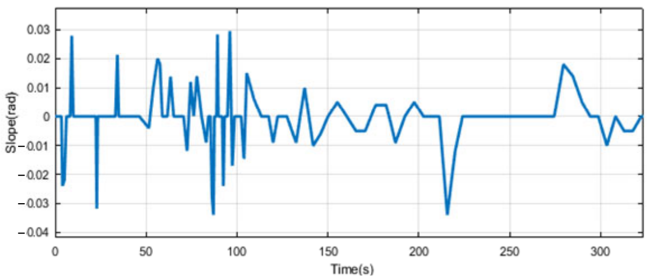
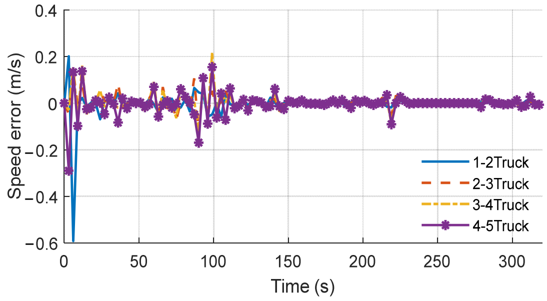
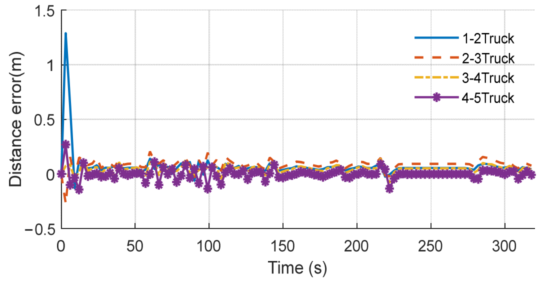


Figure 7. Road slope of the chosen highway section.

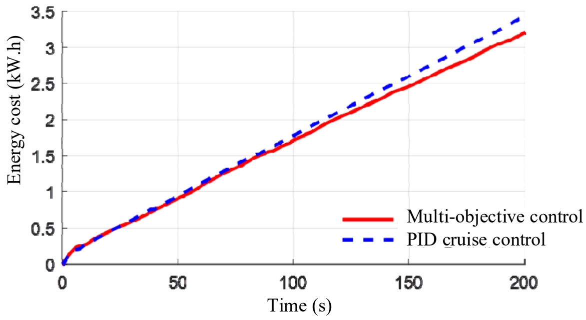
Still taking platoon 1 in Table 3 as an example, analyze the platoon's vehicle tracking performance and the energy saving performance, as shown in Figure 8.



(**a**) Speed tracking error with the proposed method



(**b**) Distance tracking error with the proposed method



(**c**) Comparison result of energy consumption

Figure 8. Test results of the heterogeneous platoon driving on the actual highway with varying slopes.

The platoon adjusted its speed from 22 m/s to the economic speed 23.5 m/s during the initial 10 s, and then drove at a constant speed of 23.5 m/s. As shown in Figure 8a,b, when driving at a constant speed, both the speed tracking error and distance tracking error can be kept within a quite small range. Even when the platoon adjusted its speed, the proposed DNMPC-based cooperative multi-objective control method could ensure that the tracking error fluctuated in a small range, and the platoon stability could be quickly achieved.

The detailed comparison of the results of the simulation test on the actual highway with varying slopes are shown in Table 5. As shown in Figure 8c and Table 5, compared with the cruise control method, the proposed multi-objective control method shows better energy saving performance and vehicle tracking performance. The energy consumption can be saved by 5.66%, while reducing vehicle tracking error.

Table 5. Comparison of the results of the heterogeneous platoon on the actual sloped road with different control method.

Control Method / Performances	The Proposed DNMPC-Based Multi-Objective Control Method	The Cruise Control Method
Average speed tracking error (m/s)	0.1203	0.2764
Average distance tracking error (m)	0.2810	0.2908
Total energy consumption (kW·h)	3.2785	3.4752

5.2.3. Test of NSGA-II-Based Weight Coefficient Optimization Method

In order to verify the effectiveness of the proposed weight coefficient optimization method, the comparative simulation test is carried out.

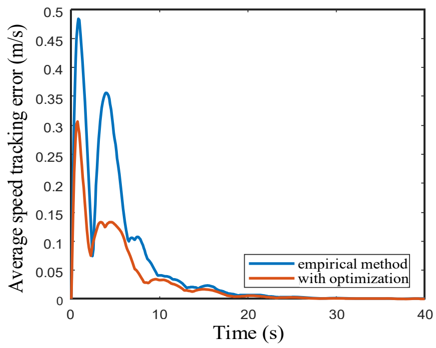
According to reference [23], the weight coefficients are designed with the empirical method, as shown in Table 6. In addition, the optimal weight coefficients are calculated for each follower with the proposed NSGA-II-based optimization method, as described in Section 4. With different weight coefficients, the performances of the heterogeneous platoon based on the multi-objective control method are shown in Figure 9. The detailed comparison results are shown in Table 7. As shown in Figure 9 and Table 7, with the proposed NSGA-II-based weight coefficient optimization method, the vehicle tracking performance and energy saving performance of the platoon can be improved simultaneously.

Table 6. Weight coefficients with the empirical method and the optimization method.

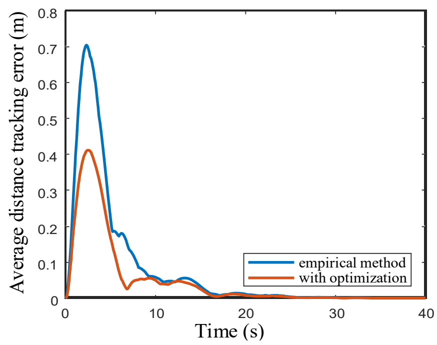
No.	Weight Coefficients with the Empirical Method	Weight Coefficients with the Optimization Method
1	*Q*1 = 5, *G*1 = 5, *W*1 = 5	/
2	*Q*2 = 5, *G*2 = 5, *W*2 = 5	*Q*2 = 3.2102, *G*2 = 1.8589, *W*2 = 4.3012
3	*Q*3 = 5, *G*3 = 5, *W*3 = 5	*Q*3 = 0.4688, *G*3 = 5.8102, *W*3 = 1.7082
4	*Q*4 = 5, *G*4 = 5, *W*4 = 5	*Q*4 = 0.1540, *G*4 = 3.7788, *W*4 = 1.2393
5	*Q*5 = 5, *G*5 = 5, *W*5 = 5	*Q*5 = 0.5830, *G*5 = 1.8529, *W*5 = 22.2115

Table 7. Comparison results of the heterogeneous platoon with different weight coefficients.

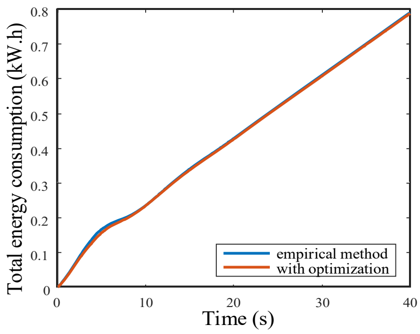
Performances	The Typical Empirical Method	The Proposed Optimization Method	Percentage of the Improvement
Average speed tracking error (m/s)	0.2272	0.1234	45.7%
Average distance tracking error (m)	0.3226	0.1996	38.1%
Total energy consumption (kW·h)	0.7903	0.7884	0.24%



(**a**) Average speed tracking error of the platoon



(**b**) Average distance tracking error of the platoon



(**c**) Total energy consumption of the platoon

Figure 9. Test results of the heterogeneous platoon with different weight coefficients.

5.3. Real Road Experiment Based on Micro-Vehicle Platoon

In order to verify the effectiveness and real-time performance of the proposed control system, a real-road experiment is conducted based on three micro-vehicles, which are manufactured by JROBOT, as shown in Figure 10**.** Vehicle 1 is a wheeled one, WARTHOG01, which acts as the leader in the platoon, and vehicle 2 and 3, Komodo, are the followers.

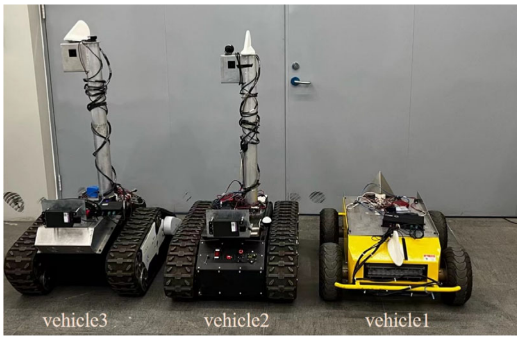


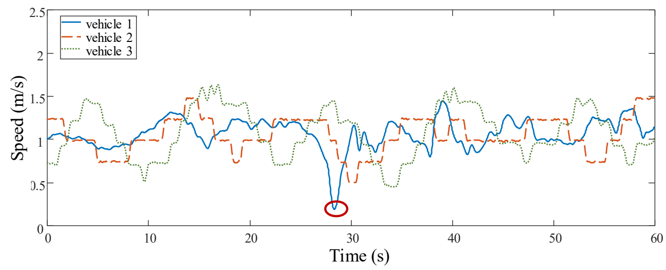
Figure 10. Three micro-vehicles for the experiment.

This experiment aims to verify the real-time computational performance of the proposed control system, and therefore an ordinary vehicle control unit (VCU) is chosen as the core controller, as shown in Figure 11a. The test field consists of a straight section and curved section, and the snapshot of road experiment is shown in Figure 11b.

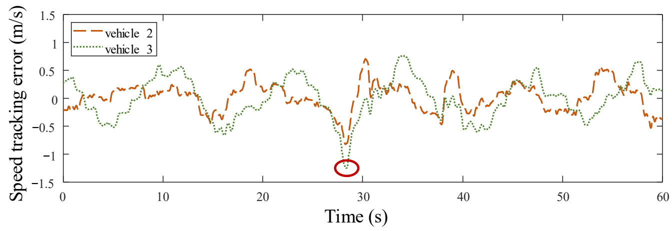
(**a**) VCU (**b**) Snapshot of the road experiment

Figure 11. Photos of the real-road experiment.

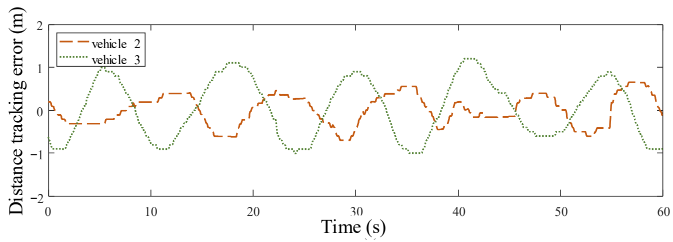
The speed trajectories of three vehicles, and the tracking error of two followers, are shown in Figure 12. The blue line represents vehicle 1, the leader, the orange dashed line for vehicle 2, and the green dotted line for vehicle 3. The platoon entered the curved section at about 28 s, so the speed of vehicle 1 decreased suddenly (blue line of Figure 12a), and speed tracking error of two followers increased (Figure 12b) but soon was regulated to within 0.5 m/s. During the whole process, the platoon was able to drive safely and stably, speed tracking error was controlled within ±0.8 m/s, and distance tracking error was controlled within ±1 m.



(**a**) Speed trajectories of three vehicles



(**b**) Speed tracking error of two followers



(**c**) Distance tracking error of two followers

Figure 12. Results of the real-road experiment.

The experiment verifies that the proposed control method can work on the VCUs of micro-vehicles, and ensure the stability of the platoon. Thus, the real-time computational requirements can be satisfied in real applications.

6. Conclusions

Aiming to improve the overall performance of a heterogeneous platoon on the highway, this paper presents a cooperative multi-objective control system, which takes four major objectives into consideration, as well as the road slope. The following conclusions can be drawn:

(1) A two-layer architecture of the multi-objective control system for heterogeneous platoons is presented. For the dynamic layer, a nonlinear model of a heterogeneous platoon is established, depicting various dynamic characteristics of vehicles and the influence of road slope and wind resistance. For the control layer, rich information is provided to distributed controllers for the calculation of the optimal control variables. The proposed architecture is the basic of multi-objective control of heterogeneous platoons.

(2) A cooperative multi-objective control strategy based on the DNMPC method is proposed, and controllers for the leader and followers are designed cooperatively. Comprehensive objective functions with multiple targets are built up, achieving integrated optimization of safety, stability, energy saving, and passenger comfort. Through comparative simulation tests on the highway with slopes, it is verified that, compared with the classic cruise control method of vehicle platoons, the proposed approach can improve the fuel economy by more than 5% and reduce tracking error simultaneously, on the premise of ensuring safety and passenger comfort.

(3) The NSGA-II-based weight coefficient optimization method is presented, to obtain the optimal weight coefficient set for each vehicle. Through comparative simulation tests, it is shown that, compared with the commonly used empirical method, multi-objective collaborative optimization capability of the heterogeneous platoon can be further improved.

(4) In the simulation tests, three types of heterogeneous platoons with different structural parameters have been tested, and the performances have been analyzed.

(5) The proposed control system was developed and equipped on three micro-vehicles. Real-road experiments show that the proposed control system can effectively work, and real-time computational requirements can be satisfied in real applications.

The quality of information transmission between controllers will greatly affect the performances of platooning control. There is an assumption in this study, which is that a V2V (vehicle-vehicle) communication network is ideal. We will further study the platooning control method with non-ideal communication in the future.

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