Fuel-saving Oriented Model Predictive Control of Truck Platoons

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***Abstract*—Fuel consumption problem of truck platoons is considered in this paper, in which a distributed model predictive controller (DMPC) based on lateral and longitudinal coupling dynamics is designed. A two-layer control structure is adopted,in which the upper layer is based on the fuel consumption model and combines the road information to plan the speed of the leading truck. Simultaneously, the tracking ability of the following trucks is considered, the optimal fuel-saving velocity of the platoon is obtained and transmitted to the lower truck control layer. A coupling controller is designed based on the five-degree-of-freedom model in the platoon control layer, co-simulation experiments are provided on joint simulation platform of Trucksim/Simulink, which the simulation results show that the fuel consumption of the platoon based on speed planning is less than that of the platoon based on constant speed cruise. While meeting the safety control of the platoon, fuel consumption has been reduced.**

***Index Terms*—truck platoon, fuel consumption, speed planning, distributed model predictive control, lateral and longitudinal coupling dynamics**

I. Introduction

Due to the rapid development of the logistics industry, the number of commercial trucks has increased, resulting in an increase in the demand for fuel. Studies have shown that the fuel efficiency in road transportation of China is approximately 25% and 10% lower than that of Europe and the United States, respectively [1]. Therefore, how to effectively improve fuel efficiency and reduce fuel consumption is the development direction of the automobile industry and one of the difficulties to be solved.

The research demonstrates that when trucks travel with closer following spacing, it not only helps alleviate traffic congestion but also reduces air resistance, leading to decreased fuel consumption for the trucks [2, 3]. During trucks driving, repetitive acceleration or deceleration leads to fuel consumption. In [4], in order to avoid unnecessary braking and acceleration during truck driving, the minimum acceleration of the truck from static to set speed is studied. In [5], the road slope and speed limit are considered, and the optimal speed is solved by constructing a quadratic optimization problem to reduce the fuel consumption of the platoon. A nonlinear model predictive control algorithm is proposed, which effectively reduces unnecessary braking and acceleration and helps the truck platoon form fuel-efficient speed profiles in [6].

It is worth noting that when planning the speed of the truck platoon, it is necessary to consider both the tracking ability of the following trucks and the road information, so as to reduce the fuel consumption under the premise of ensuring the safety of driving. A heterogeneous platoon of different masses and sizes are considered and the average platoon model is established in [7]. The distributed adaptive three-step controller is designed in [8] to ensure that the entire truck platoon can travel with the optimal speed and string stability under dynamic disturbances. A two-layer control structure is introduced in [9]. The safe velocity trajectory calculated in the upper layer and the minimum following error and safe truck spacing is ensured in the lower layer. An economical predictive cruise control method that integrates dynamic information from surrounding trucks and road conditions is presented in [10]. A fuel-efficient distributed predictive controller for homogeneous trucks is proposed in [11]. By previewing traffic information, the speed planning of fuel-efficient is realized, and the local stability and string stability are guaranteed.

Due to the existence of lateral and longitudinal coupling dynamics effects during trucks driving, it is necessary to express the coupling characteristics of trucks when modeling the truck platoon coordination controller [12, 13]. In [12], a truck model considering lateral and longitudinal coupling dynamics is established for curved road conditions. The stability and effectiveness of the controller are demonstrated. To achieve truck tracking control under complex conditions, a truck model considering lateral and longitudinal coupling dynamics

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is established in [13]. The results show that its robustness and longitudinal-lateral tracking performance are superior to controllers that do not consider coupling effects. In practice, various complex road conditions exist. To plan the fuel-saving speed of the platoon for complex road conditions and ensure the stable and safe driving of platoons is still an important issue that has not been solved. The main contribution of this study is as follows:

1) In the speed planning layer, the road conditions such as slope and curvature are taken into consideration. The speed planning is performed for the leading truck, resulting in the fuel-saving velocity for the entire truck platoon. This approach aims to reduce the fuel consumption of the platoon. Additionally, the following capabilities of the following trucks are considered to ensure that the following trucks can meet the required speed changes while maintaining the desired platoon formation.

2) In the truck platoon control layer, the coupling characteristics and safety control issues of the trucks are taken into account. By incorporating a distributed predictive control algorithm into the controller design, a solution for ensuring both economic efficiency and safety is provided.

The remainder of this paper is organized as follows: In section II, a mathematical description of the research problem and leading truck fuel consumption model is established in part A, the platoon model are proposed in part B the control objectives of truck platoon are proposed in part C. In section III, speed planning of the leading truck is designed in part A and a truck platoon model with a five-degree-of-freedom [14] model is considered and a controller based on the distributed model predictive control algorithm is designed in part B. The tracking control results and the fuel consumption of the platoon are given in section IV. Section V concludes the paper.

II. PROBLEM FORMULATION

A. Fuel Consumption Model of Leading Truck

The platoon consisting of N trucks with different masses travels on a slope and a curve road, suppose that the leading truck is uncontrolled and drives along the desired path. s_i and v_i represent the position and velocity of the ith truck, respectively, where $i = 0, 1, \cdots N-1$, $i = 0$ represents the leading truck, and the rest are the following trucks. The resistance of the truck when driving on the ramp θ includes rolling resistance, air resistance and slope resistance, while the truck is not affected by the slope resistance when driving on the curve. Fig. 1 shows the longitudinal dynamics of the single truck on the slope.

The dynamic model of the leading truck on the ramp can be expressed as the follows:

$$\begin{cases} \dfrac{ds}{dt} = v(t) \\ m\dfrac{dv}{dt} = F_e - F_{tf} - F_{aero} - F_{gra} \end{cases} \tag{1}$$

where s and v are the position and speed of truck. F_e, F_{tf}, F_{aero} and F_{gra} are the force provided by the engine, rolling

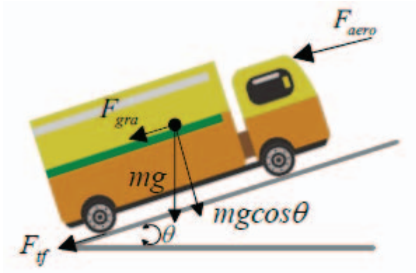

Fig. 1. The longitudinal dynamics of the single truck on the slope

resistance, air resistance and slope resistance, in which $F_{tf} = C_{tf} mg\cos\theta$, $F_{aero} = \frac{1}{2}\rho C_{aero} A v^2$, $F_{gra} = mg\sin\theta$, C_{tf} is the rolling resistance coefficient of truck; C_{aero} is the air resistance coefficient of truck; m is the total mass of truck; ρ is the air density; A is the windward aera of truck; g and θ are gravity acceleration and ramp angle.

The mechanical power of truck needs to overcome the effect of gravity and is affected by resistance, and the fuel consumption of truck is closely related to the power [15]. The mechanical power of truck can be expressed as follows:

$$P = (F_{aero} + F_{gra} + F_{tf} + F_e)\, v \tag{2}$$

The fuel consumption and mechanical power of the truck can be converted by the following formula:

$$W_{fuel} = \frac{\xi}{\kappa \cdot \psi}\left(\varepsilon E \lambda + \frac{P}{\eta \eta_{tf}}\right) \tag{3}$$

where W_{fuel} and P are the fuel consumption rate and mechanical power of the truck; ξ is the mass ratio of fuel to air; κ is the calorific value of typical diesel; ψ , ε , E and λ are the friction coefficient, engine speed, exhaust volume and conversion factor of the engine; η and η_{tf} are the efficiency parameters of the engine and the efficiency parameters of the transmission system.

B. Platoon Model

Fig. 2 shows the five-degree-of-freedom dynamics model of truck [14].

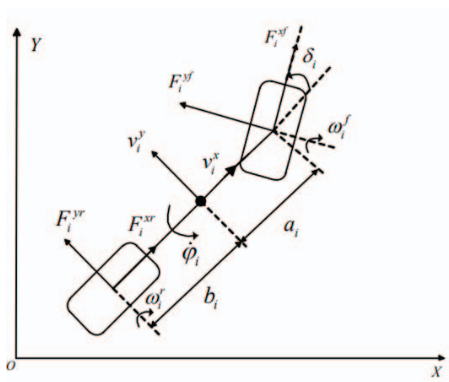

Fig. 2. The five-degree-of-freedom dynamics model of truck

The five-degree-of-freedom truck model is as follows :

$$\begin{cases} \dot{v}_i^x &= v_i^y \dot{\varphi}_i + \frac{F_i^{xf}\cos\delta_i - F_i^{yf}\sin\delta_i + F_i^{xr}}{m_i} \\ \dot{v}_i^y &= -v_i^x \dot{\varphi}_i + \frac{F_i^{xf}\sin\delta_i + F_i^{yf}\cos\delta_i + F_i^{yr}}{m_i} \\ \ddot{\varphi}_i &= \frac{\left(F_i^{xf}\sin\delta_i + F_i^{yf}\cos\delta_i\right)a_i - F_i^{yr} b_i}{I_i^z} \\ \dot{w}_i^f &= \frac{T_i^d - R_e F_i^{xf}}{J_i^f} \\ \dot{w}_i^r &= \frac{T_i^d - R_e F_i^{xr}}{J_i^r} \end{cases} \tag{4}$$

where v_i^x , v_i^y and $\dot{\varphi}_i$ are the longitudinal velocity, lateral velocity, yaw angle rate of truck. w_i^f and w_i^r are the angular velocity of front and rear wheels; m_i is the total mass of truck; I_i^z is the moment of inertia around z axis; a_i and b_i are the distances from front axle and rear axle to mass center; J_i^f and J_i^r are the moment of inertia of front and rear wheel; δ_i is the lateral control input representing steering angle of the front wheel; T_i^d is the longitudinal control input representing the torque of rear wheel; F_i^{xf}, F_i^{xr}, F_i^{yf} and F_i^{yr} are the longitudinal forces of front wheel, longitudinal forces of rear wheel, lateral forces of front wheel and lateral forces of rear wheel, respectively; R_e is the wheel rolling radius.

The Pacejka tire model [16] is applied in this paper, and the corresponding tire force in (4) can be calculated by

$$F(x) = D\sin\left(C\arctan\left(Bx - E\left(Bx - \arctan\left(Bx\right)\right)\right)\right) \tag{5}$$

where B, C, D and E are the parameters of the tire. When the input variable x is the slip ratio and the slip angle, the output variable $F(x)$ is the longitudinal tire force and the lateral tire force, respectively.

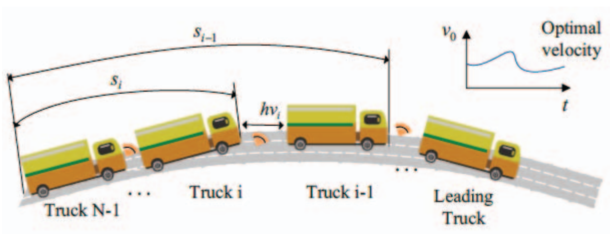

Fig. 3. The distance diagram of the truck platoon

Fig. 3 shows the distance diagram of the truck platoon, where s_i and s_{i-1} are the longitudinal positions of the i^{th} following truck and the $i-1^{th}$ following truck. The constant time-gap (CTG) spacing policy [17] and predecessor following (PF) information flow topology [18] are adopted in this paper. h is the constant headway, v_i is the current truck speed.

Fig. 4 shows the structure of the lane-keeping model, where e_i^p represents the longitudinal position error, L is the preview distance, e_i^y and e_i^φ are the lateral position error and heading angle error, respectively. R is the radius of the curve.

Define spacing error of the i^{th} truck as follows:

$$e_i^p = s_i - (s_0 - hv_i) \tag{6}$$

Denote the heading error of truck i relative to a lane as:

$$e_i^\varphi = \varphi_d - \varphi_i \tag{7}$$

where φ_d and φ_i are the actual truck heading angle and the tangential angle of the desired lane, respectively.

Denote lateral position error from the mass center of the i^{th} truck to the center of lane as e_i^y:

$$\dot{e}_i^y = v_i^x e_i^\varphi - v_i^y - L\dot{\varphi}_i \tag{8}$$

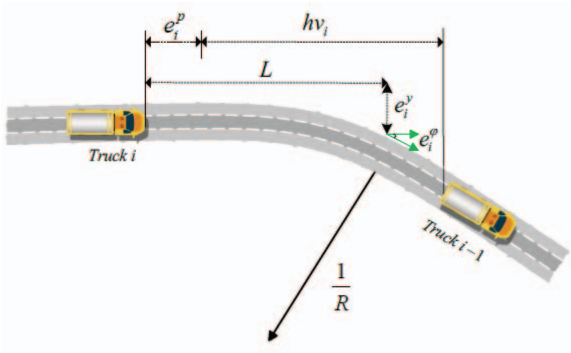

Fig. 4. The structure of the lane-keeping model

Combining the five-degree-of-freedom dynamics model of truck with the platoon model, the integrated model is as follows:

$$\begin{cases} \dot{v}_i^x &= v_i^y \dot{\varphi}_i + \frac{F_i^{xf}\cos\delta_i - F_i^{yf}\sin\delta_i + F_i^{xr}}{m_i} \\ \dot{v}_i^y &= -v_i^x \dot{\varphi}_i + \frac{F_i^{xf}\sin\delta_i + F_i^{yf}\cos\delta_i + F_i^{yr}}{m_i} \\ \ddot{\varphi}_i &= \frac{(F_i^{xf}\sin\delta_i + F_i^{yf}\cos\delta_i)a_i - F_i^{yr} b_i}{I_i^z} \\ \dot{w}_i^f &= \frac{T_i^d - R_e F_i^{xf}}{J_i^f} \\ \dot{w}_i^r &= \frac{T_i^d - R_e F_i^{xr}}{J_i^r} \\ \dot{e}_i^p &= v_i^x - v_0^x \\ \dot{e}_i^y &= v_i^x e_i^\varphi - v_i^y - L\dot{\varphi}_i \\ \dot{e}_i^\varphi &= \dot{\varphi}_{i,des} - \dot{\varphi}_i \end{cases} \tag{9}$$

C. The Control Objectives of Truck Platoon

The control objectives of the i^{th} following truck are described as follows:

1) The adjacent trucks in the platoon at time k maintain the desired spacing, and the longitudinal position error is 0:

$$\lim_{k\to\infty} \|s_{i-1}(k) - s_i(k) - hv_i\| = 0 \tag{10}$$

2) The velocity of the i^{th} following truck tracks the velocity of the leading truck, and the speed error between the following truck and the leading truck at time k is 0:

$$\lim_{k\to\infty} \|v_i^x(k) - v_0^x(k)\| = 0 \tag{11}$$

where v_0^x and v_i^x are the longitudinal velocity of the leading truck and the longitudinal velocity of the i^{th} following truck.

3) The expected truck lateral position error $e_i^y(k)$ and heading angle error $e_i^\varphi(k)$ at time k are 0:

$$\begin{cases} \lim\limits_{k\to\infty} \|e_i^y(k)\| = 0 \\ \lim\limits_{k\to\infty} \|e_i^\varphi(k)\| = 0 \end{cases} \tag{12}$$

III. CONTROLLER DESIGN

A. Speed Planning of The Leading Truck

Considering the following ability of the following trucks, the speed planning of the leading truck is carried out, and the following trucks follow the speed of the leading truck to achieve the purpose of fuel saving. The position and speed of the truck are defined as the state, which can be expressed as $x = [s, v]^T$, and the power of the engine is selected as the control input u.

Define the output:

$$y = [s, v]^T \tag{13}$$

Taking the sampling step ΔT, the discrete counterpart of (1) is as follows:

$$\begin{cases} x(k+1) = f\left(x\left(k\right), u\left(k\right)\right) \\ y(k) = x\left(k\right) \end{cases} \tag{14}$$

The control sequence in the prediction horizon is defined as:

$$u(k) = \{u(k|k), \cdots u(k+H-1|k)\} \tag{15}$$

where H is the prediction horizon, $k+j|k$ is the prediction of k time to $k+j$ time.

The optimization problem 1 is described as follows:
Problem 1

$$\begin{aligned} &\underset{u(k)}{minimize}\, J = \sum_{k=0}^{H-1} W_{fuel}\left(x\left(k\right), u\left(k\right)\right) \\ &s.t. \\ &x(k+j+1|k) = f\left(x(k+j|k), u(k+j|k)\right) \\ &y(k+j|k) = x(k+j|k) \\ &y(k|k) = y(k) \\ &F_{e,\min} \leq F_e \leq F_{e,\max} \\ &v_{\min} \leq v \leq v_{\max} \\ &a_{\min} \leq a \leq a_{\max} \end{aligned} \tag{16}$$

where $F_{e,\max}$ and $F_{e,\min}$ represent the upper and lower bounds of truck power in the truck platoon, $a_{\max}$ and $a_{\min}$ are the upper and lower bounds of truck acceleration in the truck platoon, $v_{\max}$ and $v_{\min}$ represent the speed limit of the highway.

B. Distributed Controller Design

Under the DMPC framework, a global optimization problem is transformed into a local optimization problem of each truck, i.e., all the following trucks solve its own optimization problem synchronously.

Define the state:

$$x_i = [v_i^x \;\; v_i^y \;\; \dot{\varphi}_i \;\; \omega_i^f \;\; \omega_i^r \;\; e_i^p \;\; e_i^y \;\; e_i^{\varphi}]^T \tag{17}$$

Define the output:

$$y_i = [v_i^x \; e_i^p \; e_i^y \; e_i^{\varphi}]^T \tag{18}$$

The control inputs are the driving/brake torque of rear wheel, and the steering angle of the front tires, respectively:

$$u_i = [T_i^d \;\; \delta_i]^T \tag{19}$$

Denote T_s as the sampling time. Then, the discrete counterpart of (9) is as follows:

$$\begin{cases} x_i(k+1) = f_i(x_i(k), u_i(k)) \\ y_i(k) = C_i x_i(k) \end{cases} \tag{20}$$

where $C_i = diag(1,0,0,0,0,1,1,1)$, $i = 1, 2, \cdots N$.

According to (20), the output of the following trucks in the platoon is:

$$y_{i,des}\left(k\right) = \left[\; v_{i,des}^x\left(k\right) \; e_{i,des}^p\left(k\right) \; e_{i,des}^y\left(k\right) \; e_{i,des}^{\varphi}\left(k\right) \;\right]^T \tag{21}$$

where $v_{i,des}^x\left(k\right)$ is the desired longitudinal velocity of the i^{th} truck. In order to guarantee that the truck in the platoon can track the longitudinal velocity of the leading truck, set $v_{i,des}^x\left(k\right) = v_0$. $e_{i,des}^p\left(k\right)$, $e_{i,des}^y\left(k\right)$ and $e_{i,des}^{\varphi}\left(k\right)$ represent the longitudinal expected position error, lateral expected position error and expected heading angle error of the i^{th} truck respectively.

For each truck i, The tracking error is defined as :

$$e_i(k) = y_i(k) - y_{i,des}(k) \tag{22}$$

Define the sequence of control inputs as:

$$U_i(k) = \{U_i(k|k), \cdots U_i(k+N_p-1|k)\} \tag{23}$$

where N_p is the prediction horizon. Note that $k+j|k$ denotes the predicted value at time instant $k+j$ predicted at time instant k.

The optimization problem of each following truck is as follows:
Problem 2

$$\underset{U_i(k)}{minimize}\, J_i\left(e_i(k), U_i\left(k\right)\right) \tag{24a}$$

$$s.t.$$

$$x_i(k+j+1|k) = f_i(x_i(k+j|k), u_i(k+j|k)) \tag{24b}$$

$$y_i(k+j|k) = C_i x_i(k+j|k) \tag{24c}$$

$$y_i\left(k|k\right) = y_i\left(k\right) \tag{24d}$$

$$-T_{i,min}^d \leq T_i^d(k+j|k) \leq T_{i,max}^d \tag{24e}$$

$$-\delta_{i,min} \leq \delta_i(k+j|k) \leq \delta_{i,max} \tag{24f}$$

where

$$J_i\left(e_i\left(k\right), U_i\left(k\right)\right) = \sum_{j=0}^{N_p-1} \left(\left\| e_i\left(k+j|k\right) \right\|_{Q_i}^2 + \left\| u_i\left(k+j|k\right) \right\|_{R_i}^2 \right) \tag{25}$$

In the objective function J_i, Q_i and R_i are the weight matrices to be determined, (24e) and (24f) are the control constraints.

IV. SIMULATION AND RESULT ANALYSIS

A truck platoon consists of four trucks, i.e., one leading truck, and three following trucks. Co-simulation experiments are provided on joint simulation platform of Trucksim/Simulink. The parameters of trucks are shown in TABLE I. The parameters of the distributed controllers are shown in TABLE II.

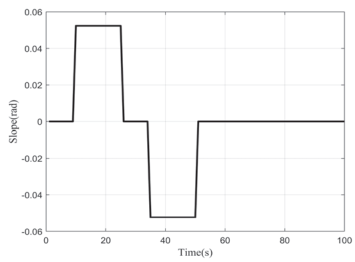

Fig. 5. Slope of road

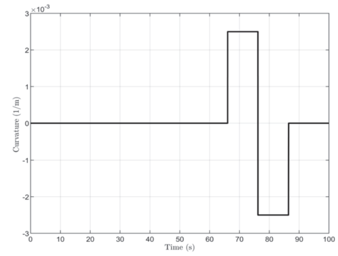

Fig. 6. Curvature of road

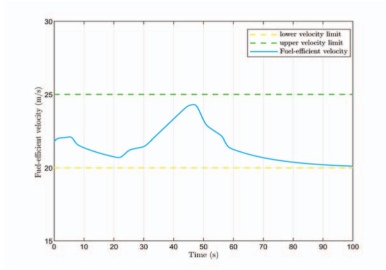

Fig. 7. The profile of the fuel-efficient velocity

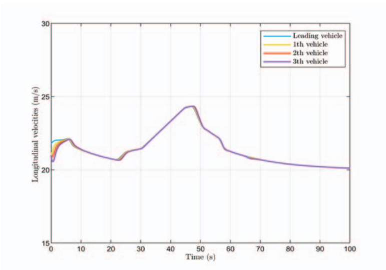

Fig. 8. Longitudinal velocities of the platoon

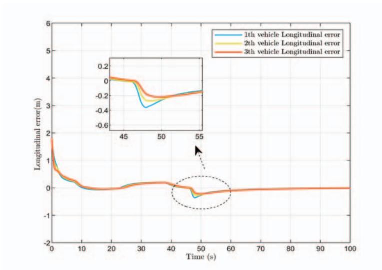

Fig. 9. Longitudinal error of the platoon

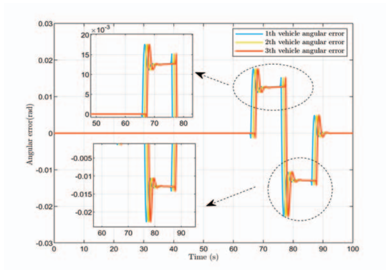

Fig. 10. Angle error of the following trucks

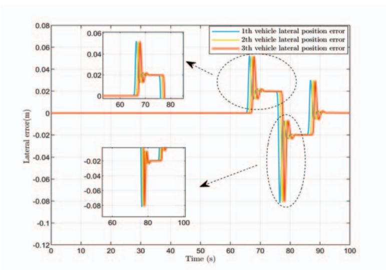

Fig. 11. Lateral error of the platoon

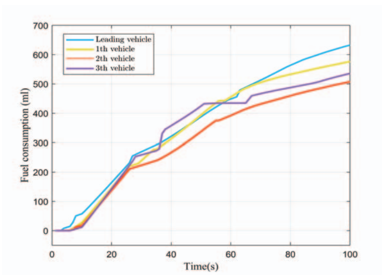

Fig. 12. Consumption based on speed planning

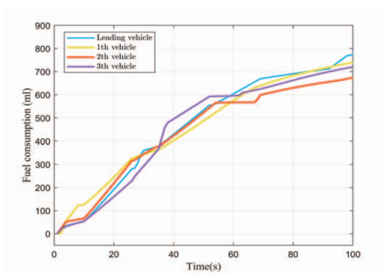

Fig. 13. Consumption based on constant speed

TABLE I
THE PARAMETERS OF TRUCKS

Parameters	Value	Parameters	Value
ξ	1	I_z	130421.8 $(kg \cdot m^2)$
κ	44	a	3.5 (m)
ψ	737	b	1.5 (m)
E	33	g	9.8 m/s^2
ε	0.2	R_e	0.51 (m)
λ	5	J_f	24 $(kg \cdot m^2)$
η	0.9	J_r	48 $(kg \cdot m^2)$
η_{tf}	0.4		

TABLE II
THE PARAMETERS OF THE DISTRIBUTED CONTROLLERS

Parameters	Value
N_p	7
T_s	0.01 (s)
Q_i	$10^5 \times \begin{bmatrix} 5 & 0 & 0 & 0 \\ 0 & 70 & 0 & 0 \\ 0 & 0 & 50 & 0 \\ 0 & 0 & 0 & 50 \end{bmatrix}$
R_i	$\begin{bmatrix} 0.06 & 0 \\ 0 & 1.5 \times 10^6 \end{bmatrix}$
h	0.8

A. *Velocity Optimization of The Leading Truck*

The slope information is shown in Fig. 5, and the curvature information is shown in Fig. 6. The inclination angles of the uphill and downhill roads are $3°$ and $-3°$, respectively. The curvature of the curve is $\pm$ 0.0025, and the road adhesion coefficient is 0.85.

The profile of the fuel-efficient velocity of the leading truck is shown in Fig.7. The road speed limit $v_{\min}$ and $v_{\max}$ are 72 km/h and 90 km/h respectively. It can be seen from Fig. 7 that the truck velocity does not exceed the speed limit under this road condition and meets the requirements of road speed limit.

B. *Platoon Control*

Fig. 8 shows the longitudinal velocities of the platoon, in which the initial speed of the leading truck is 22 m/s, and the initial speed of the three following trucks are 21 m/s. It can be seen from the Fig. 8 that the following trucks can track the velocity well. In Fig. 9, the maximum longitudinal error of the platoon fluctuates within $\pm$ 0.4 m, and finally tends to 0. Fig. 10 is the heading angle error of the following trucks, and the maximum deviation is not more than 0.025 rad, which meets the control requirements. Fig. 11 shows the lateral position error of the following trucks, and the maximum error is about 0.08 m.

C. Fuel Consumption of Platoons

Fig. 12 is the fuel consumption of the platoon based on the speed planning, and Fig. 13 is the fuel consumption of the platoon based on the constant speed setting. The fuel consumption comparison is given in TABLE III.

TABLE III
THE FUEL CONSUMPTION COMPARISON

Parameters	Speed planning(ml)	Constant speed(ml)
leading truck(16000kg)	649.6	763
1th truck(18000kg)	597.8	729.8
2th truck(18000kg)	555.7	664.4
3th truck(20000kg)	579.5	709.9
total fuel consumption	2382.6	2867.1

From the fuel consumption data based on speed planning, it can be seen that there is about 8 % fuel saving rate of following truck 1 compared with the leading truck. In the case of the same quality truck, the rear truck can save about 7 % fuel than the front truck. The air resistance coefficients of the following truck 2 and the following truck 3 are roughly equal. When the mass of the following truck 3 is greater than that of the following truck 2, the fuel consumption is slightly larger. Compared with the total fuel consumption, the fuel saving rate of the method based on speed planning can reach 16.9 % compared with the method of constant speed.

V. CONCLUSION

Fuel saving and safety control of platoons is studied in this paper. By considering the tracking ability of the following trucks, the speed planning of the leading truck is carried out. In the control layer, the distributed model predictive controller is adopted. Simulation results show that the strategy has less fuel consumption than constant speed cruise while ensuring the safety control of the platoon.

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