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Trajectory Planning and Tracking Control of Vehicle Obstacle Avoidance based on Optimization Control

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Abstract: For the problem of vehicle obstacle avoidance control, a steering obstacle avoidance method based on optimization idea is designed. In the research of obstacle avoidance path planning method, a design method with three-segment sinusoidal lateral acceleration is adopted, combining with various practical constraints of vehicle and safe distance, an optimization solution method of obstacle avoidance trajectory is presented, which takes obstacle avoidance time as the optimal objective. Based on the established two-degree-of-freedom vehicle dynamics model, a tracking controller with moving horizon idea is designed. Using the vehicle dynamics simulation software veDYNA, the scene of vehicle lane change and obstacle avoidance is constructed. The effectiveness and control performance of this method are illustrated by simulation.

Key Words: Vehicle obstacle avoidance, steering control, trajectory optimization, moving horizon

1 Introduction

At present, automotive intelligence has become a hot research topic in the automotive industry and vehicle engineering field. With the continuous increase of vehicle ownership, road congestion and the rapid expansion of driver groups, the frequency of traffic accidents is increasing. Among them, vehicle collisions have led to a considerable proportion of major traffic accidents. Vehicle obstacle avoidance control technology in emergencies or non-emergencies has been the major focus of academic attention and extensive research.

In the existing vehicle obstacle avoidance control technology research, usually adopts the obstacle avoidance path planning and tracking control method. It is the most effective control scheme for vehicle obstacle avoidance at present. For optimal trajectory planning, it usually includes artificial potential field method, intelligent computing method, landmark method and pseudo-spectral method. In [1], the obstacle avoidance problem had been transformed into a multi-objective optimization problem, and the optimal obstacle avoidance trajectory was obtained by solving the optimization problem. Reference [2] calculated a set of feasible trajectories according to the predefined path points and information of the obstacles. By comparing the smoothness, safety and stability of each feasible trajectory, the optimal driving trajectory was determined to achieve real-time path planning. These two methods were combined with various non-holonomic constraints, planning the optimal trajectory, had a certain practical significance. Planning the danger level of obstacles was also an effective method. In [3] the danger area was calculated that may collide with the obstacle according to the relative speed of the obstacle, and then the safe driving strategy was formulated that can effectively avoid the obstacle according to this area. The definition of danger area provides a criterion for judging the danger degree of obstacles. In [4] the danger degree of obstacles was taken as the input signal of the fuzzy controller to solve the problem of autonomous obstacle avoidance of vehicles. Based on the established vehicle dynamics model and the obstacle avoidance path constraint conditions, the pseudo-spectral method was used to design the optimal obstacle avoidance path [5]. After planning a safe and effective trajectory, it is necessary to adopt corresponding driving operations to track the expected path. In order to ensure the real-time performance and stability of the system, many control methods had been proposed, including traditional PID control, feedback linearization control, fuzzy control, model prediction control, etc. [6-9]. Reference [10] proposed the path planning method by polynomial function, acceleration threshold and anti-collision condition, and the tracking control law method was designed by moving horizon, and the control effect was good. Furthermore, accuracy and rapidity of trajectory optimization are enhanced with the use of the combination of adaptive scheme and the Gauss pseudospectral method [11].

For the problem of vehicle steering obstacle avoidance control, a vehicle obstacle avoidance trajectory planning and tracking control method is designed in this paper based on the idea of optimal control, and simulation verification is carried out in the software of veDYNA.

The second part describes the vehicle obstacle avoidance control scheme, the third part describes the trajectory optimization calculation method, the fourth part designs the tracking control law based on model predictive control, the fifth part illustrates the performance of the method through simulation and the sixth part concludes the paper.

2 Obstacle Avoidance Control Scheme

In order to avoid the obstacles on the road ahead of the vehicle, there are usually two kinds of vehicle obstacle avoidance strategies: one is to reduce the speed by pressing the brake pedal to stop the vehicle before reaching the obstacle and avoid collision; the other is to steer the vehicle by adjusting the steering wheel to avoid collision. After avoiding obstacles and reaching a safe distance, the vehicle can choose to return to the original lane or continue on the road parallel to the original lane. In this study, for the obstacles that suddenly appear in front of the vehicle, the strategy of avoiding obstacles is to keep the longitudinal

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speed of the vehicle unchanged, only steering the steering wheel, and keep the path parallel to the original road after avoiding obstacles. At the same time, in the study of the optimal trajectory planning for obstacle avoidance, a curve planning method with three-segment sinusoidal lateral acceleration is adopted. Under the constraints of lateral acceleration and speed, vehicle trajectory under the optimal time objective of obstacle avoidance is obtained by optimizing solution. In the design of tracking controller for the optimal obstacle avoidance trajectory, based on the 2-degree-of-freedom vehicle dynamics model and the moving horizon control idea, the tracking controller based on model predictive control is designed to steer the steering wheel to achieve obstacle avoidance. By setting obstacle avoidance scenarios in veDYNA, the effectiveness and performance of the proposed control method are verified.

This paper assumes that the vehicle sensing system can provide the required position, velocity, acceleration and other information for the vehicle itself, and the perception system can provide environmental information, such as road boundary, obstacle location and relative velocity, etc. That is to say, the needed vehicle, obstacle and environmental information in this study can be obtained by sensor measurement or other estimation algorithm. The block diagram of obstacle avoidance control scheme in this paper is shown in Figure 1.

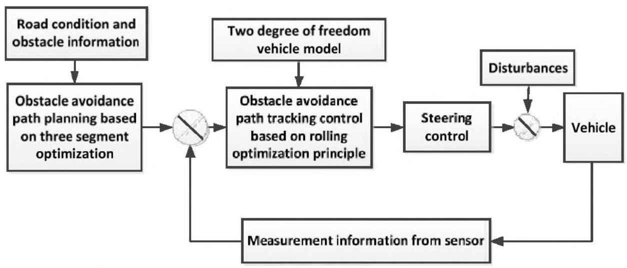

Figure 1: Control scheme of obstacle avoidance

3 Obstacle Avoidance Path Planning based on Three Segment Optimization

3.1 Obstacle Avoidance Path Planning Strategy

Based on the on-board sensor system, when the vehicle detects obstacles on the front lane, it adopts steering wheel to avoid obstacles in a variety of ways, such as Path 1 and Path 2 in Figure 2. However, the effect of these two paths on obstacle avoidance is different. Path 1 is that the lateral displacement of the vehicle has exceeded the lateral position of the obstacle before the longitudinal displacement of the vehicle reaches the obstacle, and the safety of obstacle avoidance has been realized. Path 2 is that the lateral displacement of the vehicle exceeds the lateral position of the obstacle after the longitudinal displacement of the vehicle reaches the obstacle. Although obstacle avoidance can also be achieved, the efficiency and safety of obstacle avoidance path 1 are better from the safety point of view.

In this paper, the concept of safe distance between vehicle and obstacle is introduced, that is, the longitudinal position difference between vehicle and obstacle. As can be seen from Figure 2, for the trajectories similar to Path 1, they all satisfy the constraint that the longitudinal displacement of the planned path is less than the safe distance. Under this constraint, the time optimal path curve of obstacle avoidance will be designed, which is also the expected input path of the follow-up tracking controller.

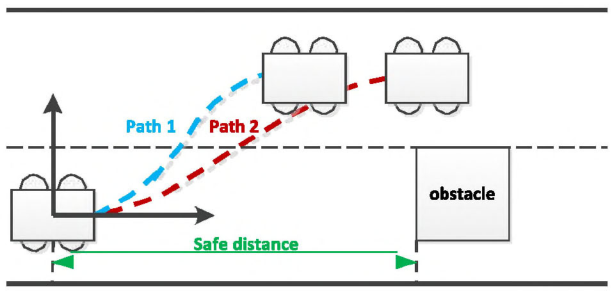

Figure 2: Schematic diagram of obstacle avoidance path planning strategy

3.2 Optimization Calculation of Obstacle Avoidance Path

For the paths similar to path 1 in Figure 2, the form of planning curve is also diverse. In this paper, a three-segment sinusoidal lateral acceleration curve is designed, which is divided into acceleration section, uniform section and deceleration section, and the acceleration section and deceleration section are designed as symmetrical sinusoidal form[12]. The lateral displacement curve can be obtained by quadratic integration of the lateral acceleration curve, as shown in Figure 3 (in this paper, the left channel is taken as an example). $T_1 = T_3 = T$ are the time periods of acceleration and deceleration sections, T_2 is the time period of uniform section. The planned maximum lateral acceleration is defined as a_y , the planned maximum lateral velocity is defined as v_y , and the expected lateral displacement is defined as y_{hope} . In this paper, the lateral displacement is assumed to be given in advance.

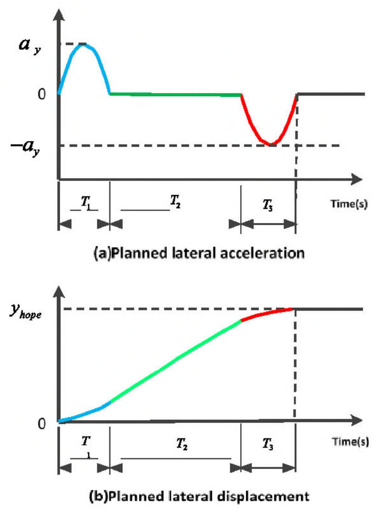

Figure 3: Planned curve of lateral acceleration and displacement

Furthermore, the planned lateral acceleration and displacement curves can be described by specific equations. In detail, the equations for acceleration, uniform and deceleration sections are shown in Tables 1 and 2.

Table 1: Planned lateral acceleration

Acceleration part	$a_y \sin(\frac{\pi}{T} t)$
Uniform part	0
Deceleration part	$-a_y \sin(\frac{\pi}{T}(t-T-T_2))$

Table 2: Planned lateral displacement

Acceleration part	$\frac{a_y T}{\pi}(t - \frac{T}{\pi}\sin(\frac{\pi}{T} t))$
Uniform part	$v_y(t-T) + a_y T^2 / \pi$
Deceleration part	$\frac{a_y T}{\pi}(t+T_2+\frac{T}{\pi}\sin(\frac{\pi}{T}(t-T-T_2)))$

Further, according to the amplitude relationship of each stage of planning curve, the steering obstacle avoidance time can be calculated as equation (1):

$$t = T_1 + T_2 + T_3 = \frac{y_{hope}}{v_y} + \frac{v_y \pi}{2a_y} \tag{1}$$

And equation (2) holds:

$$T_1 = T_3, T_2 = \frac{y_{hope}}{v_y} - \frac{v_y \pi}{2a_y} \tag{2}$$

To sum up, by taking steering avoidance time as the objective, lateral acceleration and lateral velocity as the variables to be optimized, the following optimization problem can be established (e.g. (3)), under the conditions of satisfying the restriction of avoidance curve on driver comfort (i.e., the restriction of lateral acceleration and lateral velocity) and that the longitudinal displacement of planned path terminal is less than the restriction of safe distance.

$$\min(t) = \min(\frac{y_{hope}}{v_y} + \frac{v_y \pi}{2a_y})$$
$$s.t. \begin{cases} \frac{v_y \pi}{2a_y} > 0 \\ \frac{y_{hope}}{v_y} - \frac{v_y \pi}{2a_y} \geq 0 \\ 0 \leq v_y \leq v_{y\max} \\ 0 \leq a_y \leq a_{y\max} \\ (\frac{y_{hope}}{v_y} + \frac{v_y \pi}{2a_y}) v_x < X_{safe} \end{cases} \tag{3}$$

Among them, the maximum lateral velocity and lateral acceleration allowed by the vehicle control system are defied as $v_{y\max}$ and $a_{y\max}$, the longitudinal velocity of vehicle (assumed to be constant) is defined as v_x, and X_{safe} is defined as the safety distance which is preset.

Remark 1: Considering that the steering wheel angle has the sinusoidal characteristics when the driver steers to avoid obstacles [10], this paper chooses sinusoidal planning curve of lateral acceleration. Of course, other forms of planning curves can also be selected, and the obstacle avoidance strategies and optimization methods proposed in this paper can also be used to solve the optimization problem.

Remark 2: In this study, the shape of obstacles and the trajectory of obstacle avoidance with longitudinal displacement exceeding the safe distance are not considered. In contrast, the proposed obstacle avoidance control strategy in this paper is conservative, but the obstacle avoidance trajectory selected in this paper is the most "safe" and "efficient" one. Of course, the shape of obstacles can also be taken into account in the form of geometric constraints in the optimization problem, and the optimal trajectory of obstacle avoidance under certain optimization objective can be obtained. This paper does not do in depth study here.

4 Obstacle Avoidance Path Tracking Control based on Rolling Optimization Principle

4.1 2-Degree-of-Freedom Bicycle Model

To describe the lateral and yaw motions of the vehicle, the 2-degree-of-freedom bicycle model is used. With the assumption of $\cos\delta_f \approx 1$, the equations are given below

$$\begin{aligned} m\dot{v}_y(t) + mv_x w(t) &= F_{yf}(\alpha_f(t)) + F_{yr}(\alpha_r(t)) \\ I_z \dot{w}(t) &= aF_{yf}(\alpha_f(t)) - bF_{yr}(\alpha_r(t)) \end{aligned} \tag{4}$$

where m is the vehicle mass, v_y is the lateral velocity, w is the yaw velocity, I_z is the yaw moment of inertia, a is the distance from center of gravity (COG) to front axle, b is the distance from COG to rear axle, F_{yf} and F_{yr} are the front and rear lateral tire forces respectively. The rational tire model is employed to derive the front and rear lateral tire forces F_{yf} and F_{yr}, and is written as follows.

$$F_y(\alpha(t)) = -\frac{\mu F_z}{\mu_0 F_{z0}} \frac{\gamma_z}{\gamma_\lambda \lambda^2 + 1} \frac{C_\alpha}{\gamma_\alpha \alpha^2(t) + 1} \alpha(t) \tag{5}$$

where, F_z is the vertical tire load, F_{z0} is the nominal tire load, μ is the road friction coefficient, μ_0 is the nominal road friction coefficient, λ is the longitudinal slip, C_α is the tire cornering stiffness, α is the wheel side slip angle, and $\gamma_z, \gamma_\lambda, \gamma_\alpha$ are model parameters. Given that only the lateral and yaw dynamics of the vehicle are considered in this study, the longitudinal slip λ is set to zero, and set $\mu = \mu_0$. Further, an approximation method based on the first order Taylor expansion is used for the front and rear wheel side slip angles at the linearization points $\alpha_f = 0$ and $\alpha_r = 0$. The front and rear lateral forces can be described as follows:

$$F_{yf}(t) = F_{yf}(0) + \frac{\partial F_{yf}}{\partial \alpha_f}\Big|_{\alpha_f=0}(\alpha_f - 0) = -C_f \alpha_f(t)$$
$$F_{yf}(t) = F_{yr}(0) + \frac{\partial F_{yr}}{\partial \alpha_r}\Big|_{\alpha_r=0}(\alpha_r - 0) = -C_r \alpha_r(t) \quad (6)$$

where $C_f = \frac{F_{zf}\gamma_{zf}C_f}{F_{zf0}}$ and $C_r = \frac{F_{zr}\gamma_{zr}C_r}{F_{zr0}}$. The wheel side slip angles can be approximated as:

$$\alpha_f(t) \approx \frac{v_y(t)}{v_x} + \frac{a w(t)}{v_x} - \delta_f(t), \alpha_r(t) \approx \frac{v_y(t)}{v_x} - \frac{b w(t)}{v_x} \quad (7)$$

From equations (4) to (7), the linearized state space equation can be described as follows:

$$\begin{pmatrix} \dot{v}_y(t) \\ \dot{w}(t) \end{pmatrix} = \begin{pmatrix} -\frac{C_f + C_r}{m v_x} & -\frac{aC_f - bC_r}{m v_x} - v_x \\ \frac{aC_f - bC_r}{I_z v_x} & -\frac{a^2 C_f + b^2 C_r}{I_z v_x} \end{pmatrix} \begin{pmatrix} v_y(t) \\ w(t) \end{pmatrix} + \begin{pmatrix} \frac{C_f}{m} \\ \frac{aC_f}{I_z} \end{pmatrix} \delta_f(t) \quad (8)$$

The kinematic equations of the vehicle are

$$\dot{x}(t) = v_x(t)\cos\psi(t) - v_y(t)\sin\psi(t)$$
$$\dot{y}(t) = v_x \sin\psi(t) + v_y(t)\cos\psi(t) \quad (9)$$

where, x and y are the longitudinal and lateral displacements of the vehicle in ground-fixed axes, respectively. The yaw displacement ψ is the direction of the longitudinal axis of the vehicle. When ψ is small, the kinematic equation (9) can be approximated as:

$$\dot{x}(t) = v_x(t) - v_y(t)\psi(t)$$
$$\dot{y}(t) = v_x(t)\psi(t) + v_y(t) \quad (10)$$

The following fourth order state space equation is given:

$$X(t) = \bar{A}X(t) + \bar{B}\delta(t) \quad (11)$$

$$\bar{A} = \begin{pmatrix} -\frac{C_f + C_r}{m v_x} & -\frac{aC_f - bC_r}{m v_x} & 0 & 0 \\ -\frac{aC_f - bC_r}{I_z v_x} & -\frac{a^2 C_f + b^2 C_r}{I_z v_x} & 0 & 0 \\ 1 & 0 & 0 & v_x \\ 0 & 1 & 0 & 0 \end{pmatrix}, B = \begin{pmatrix} \frac{C_f}{mG} \\ \frac{aC_f}{I_z G} \\ 0 \\ 0 \end{pmatrix}$$

Defining the output:

$$Y(t) = \bar{C}X(t) = \begin{pmatrix} 0 & 0 & 1 & 0 \end{pmatrix} X(t) = y(t) \quad (12)$$

Summarizes the equation of vehicle dynamics as below:

$$\dot{X}(t) = \bar{A}X(t) + \bar{B}\delta(t)$$
$$Y(t) = CX(t) \quad (13)$$

The continuous-time equations (13) can be converted to the discrete-time equation using the 'zoh' discretization method with the sampling period T_s:

$$X(k+1) = \bar{A}X(k) + \bar{B}\delta(k)$$
$$Y(k) = CX(k) \quad (14)$$

4.2 Tracking Control based on Model Predictive Control

According to the current vehicle states and the driving experience, the driver has the ability to predict the future vehicle states. In this case, the discrete-time state space equation $X(k+1) = AX(k) + B\delta(k)$ is used to predict the future states of the vehicle from the instance $k+1$ to $k+N_p$. When the sampling time exceeds the control horizon N_u .the control input is assumed to remain constant up to the prediction horizon, which is:

$$\delta(k+N_u-1) = \delta(k+N_u) = \delta(k+N_u+1) = \cdots = \delta(k+N_p-1)$$

By defining the vectors and matrices as follows:

$$Y_p(k) = \begin{pmatrix} Y(k+1) \\ Y(k+2) \\ \vdots \\ Y(k+N_u) \\ \vdots \\ Y(k+N_p) \end{pmatrix} \qquad U(k) = \begin{pmatrix} \delta(k) \\ \delta(k+1) \\ \vdots \\ \delta(k+N_u-1) \end{pmatrix}$$

$$S_x = \begin{pmatrix} CA \\ CA^2 \\ \vdots \\ CA^{N_u} \\ \vdots \\ CA^{N_p} \end{pmatrix} \qquad S_u = \begin{pmatrix} \bar{CB} & & 0 \\ \vdots & \cdots & \vdots \\ CA^{N_u-1}B & \cdots & CB \\ \vdots & \cdots & \vdots \\ CA^{N_p-1}B & \cdots & C\sum_{i=1}^{N_p-N_u+1} A^{i-1}B \end{pmatrix}$$

The N_p steps of the prediction output equation can be summarized as:

$$Y_p = S_x X(k) + S_u U(k) \quad (15)$$

Various cost functions are used in literature. In this study, the considered cost function is focused on the path tracking performance and optimal steering angle. The cost function in equations (16) can be described as:

$$J(k) = \sum_{i=1}^{N_p} \left\| Y(k+i) - r_g(k+i) \right\|^2_{\Gamma_{y,i}} + \sum_{i=1}^{N_u} \left\| \delta(k+i-1) \right\|^2_{\Gamma_{u,i}} \quad (16)$$

And the optimization problem is:

Problem 1

$$\min_{U(k)} J(k)$$

subject to vehicle dynamics

$$Y_p = S_x X(k) + S_u U(k)$$

where, $\Gamma_{y,i}$ and $\Gamma_{u,i}$ are weight coefficients, $r_g(k+i)$ is the reference lateral displacement.

5 Simulation Research and Analysis

In this part, based on simulation software veDYNA, a virtual vehicle obstacle avoidance scene is set up to verify the effectiveness and performance of the design method in this paper.

5.1 Simulation Scene and Parameters

It is assumed that the vehicle runs in the right lane of the two lanes in the same direction, and the longitudinal speed is a constant one. When the vehicle sensor detects the obstacle, the vehicle trajectory planning of left lane steering is started, and the steering trajectory tracking and obstacle avoidance are realized by the model predictive controller. The road condition and vehicle parameters are shown in Table 3 and Table 4.

Table 3: Road condition parameters

Parameter	Value
Lane width	3.5m
Longitudinal velocity	14m/s
Safe distance	62m
Lateral maneuvering displacement	3.5m
Obstacle	Rectangle (long 10m,width 1.75m)
Maximum allowable lateral acceleration	1.2m/s^2
Maximum allowable lateral velocity	2m/s

Table 4: Vehicle parameters

Parameter	Value
m	1296kg
I_z	1750kgm^2
a	1.25m
b	1.32m
C_f	100700N/rad
C_r	86340N/rad
G	20.4596

5.2 Simulation Results and Analysis

Through optimization calculation, the maximum lateral acceleration of the optimal obstacle avoidance trajectory is 1.2m/s^2, the maximum lateral velocity is 1.6351m/s, and the optimal time of steering obstacle avoidance is 4.2809s. The curves of lateral acceleration, lateral velocity and lateral displacement are shown in Figure 4. Figure 5 shows the relationship of vehicle, obstacle and planning trajectory in the whole scene. Figure 6 shows the tracking control effect based on model predictive control.

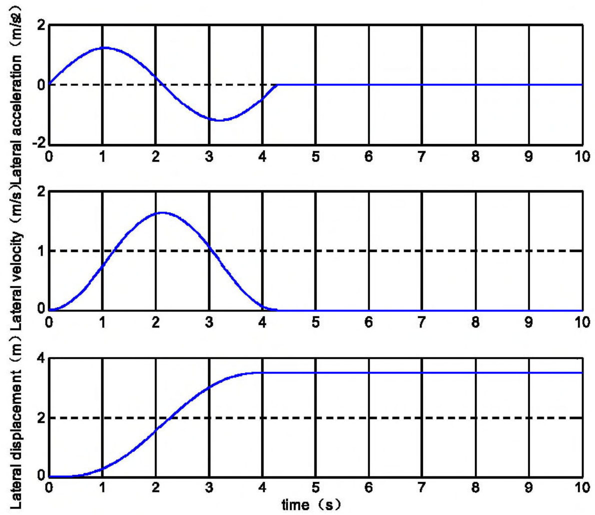

Figure 4: Planned curves of lateral acceleration, velocity and displacement

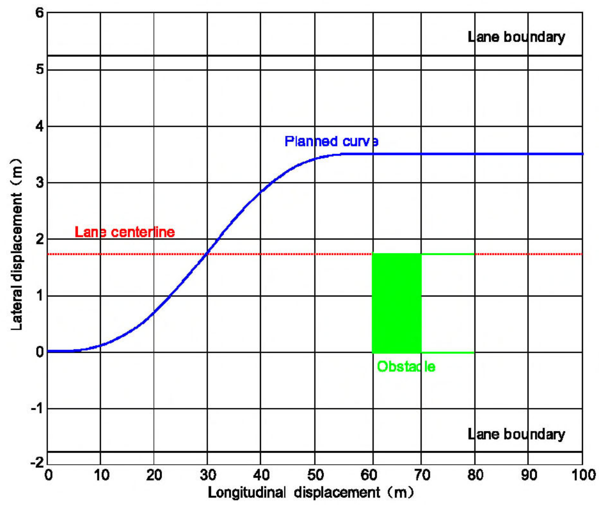

Figure 5: Planned displacement curve of vehicle obstacle avoidance

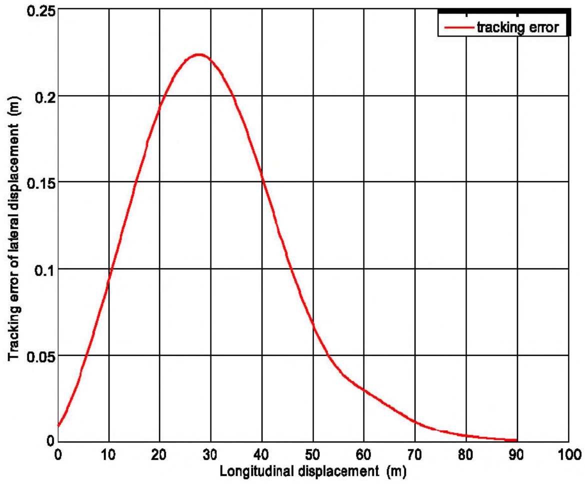

Figure 6: The tracking control effect based on model predictive control

From the simulation results based on veDYNA, we can see that, the designed model predictive controller could track the planned obstacle avoidance path very well, and the tracking error maximum of lateral displacement is less than 0.23m. The reason for the tracking error maybe the accuracy of the established 2-degree-of-freedom bicycle model has certain deviation with the vehicle model in veDYNA, and another reason maybe the parameters of MPC controller are not the optimal ones.

6 Conclusions

This paper designs a vehicle obstacle avoidance control method based on steering and lane changing, and divides the obstacle avoidance process into two parts: trajectory planning based on optimization and trajectory tracking control based on rolling optimization. Based on the three-segment sinusoidal curve of lateral acceleration, a time-optimal trajectory optimization problem with multiple constraints is established. The optimal trajectory of obstacle avoidance can be obtained by optimization solution. A two-degree-of-freedom vehicle control model is established, and an optimal trajectory tracking control law based on model predictive control is designed to achieve effective obstacle avoidance. The vehicle obstacle avoidance scenario is established in software veDYNA, which verifies the control method proposed in this paper. In the follow-up study, the obstacle avoidance trajectory and tracking control method based on optimization idea will be further studied in combination with vehicle dynamics and kinematics model.

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