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Collision-Free Path Planning for Intelligent Vehicles Based on Bézier Curve

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ABSTRACT Intelligent vehicles are expected to avoid collision through emergency lane change when a vehicle suddenly appears. Therefore, it is very meaningful to plan a path for collision-free lane change with a vehicle in front, which strikes a balance between vehicle performance and driving comfort. In this paper, a path planning method is designed based on fifth-order Bézier curve for lane change with a vehicle in front. Firstly, the boundaries were determined to ensure the fast response to the changing environment and driving comfort. Then, a multi-objective optimization function was set up, considering the curvature at the start point, the maximum curvature, the angle between path centre and road axis (the maximum swing angle), and the lane change time. Next, the coordinates of the control points that determine the curve shape were solved, and thus the optimal path was set up based on the fifth-order Bézier curve. Simulation results show that the proposed method could output suitable collision-free paths for lane change at different vehicle velocities. The research results shed new light on the dynamic path planning in actual traffic environment and enjoy great application value.

INDEX TERMS Intelligent vehicle, collision avoidance, path planning, Bézier curve, multi-objective optimization.

I. INTRODUCTION

Intelligent vehicle is a new-generation vehicle that can respond reasonably to emergency situations, such as making an emergency lane change to avoid collision with a vehicle that suddenly appears. This emergency response function, a.k.a. collision avoidance, has attracted much attention in recent years, because it directly bears on the driving safety of intelligent vehicle [1]–[4]. To prevent colliding into a vehicle in front, the intelligent vehicle needs to plan a suitable path for lane change.

Many different path planning methods [5]–[10] have been developed for the lane change before collision avoidance. For instance, the positive and negative trapezoidal lateral acceleration (PNTLA) method [5], [6], assuming that the lateral acceleration profile consists of two opposite trapezoids with the same size for the lane change on straight road, can output a continuous-curvature path for lane change and optimize the lane change time to overcome the constraint of destination position. However, this method is not flexible enough to adjust the lane change process. The polynomial method [11], another popular way to plan the lane change path, ensures the smoothness of the planned path through the continuous curvature of the polynomial curve, but fails to solve the polynomial parameters under limited constraints or plan a suitable path without knowing the destination in advance. In addition, the artificial potential field method [12], [13] achieves fast response and closed-loop control between the algorithm and the environment, but often falls into the local optimum trap.

In recent years, the Bézier curve [14]–[19] has been widely adopted for path planning, thanks to its smooth curve and simple calculation by transforming the calculation of curve shape into the solution of coordinate points. For example, Choi *et al.* [18] developed a path planning algorithm for intelligent vehicles based on third-order Bézier curve, which satisfies the boundary and structure constraints of the road. Based on fourth-order Bézier curve, Han *et al.* [17] proposed a collision-free path planning method for mobile robots. Bae *et al.* [15] designed a feasible real-time path planning algorithm for intelligent vehicles based on fifth-order Bézier curve.

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An ideal path should strike a balance between vehicle performance and driving comfort. Therefore, this paper attempts to develop a path planning method based on fifth-order Bézier curve for lane change with a vehicle in front. Firstly, the boundaries were determined to ensure the fast response to the changing environment and driving comfort. Then, a multi-objective optimization function was set up, considering the curvature at the start point, the maximum curvature, the angle between path centre and road axis (the maximum swing angle), and the lane change time. Next, the coordinates of the control points that determine the curve shape were solved, and thus the path was set up. On this basis, the optimal path was planned for the lane change before collision avoidance. Simulation results show that the planned path was created rapidly and efficiently, and could satisfy the requirements of lane change.

The remainder of this paper is organized as follows: Section 2 analyses the features of Bézier curve in different orders; Section 3 designs and optimizes the collision-free path based on the fifth-order Bézier curve; Section 4 demonstrates the effectiveness of the planned path through simulations; Section 5 puts forward the conclusions.

II. ANALYSIS OF BÉZIER CURVE IN DIFFERENT ORDERS

Since it was proposed by Pierre Bézier in 1962, the Bézier curve [15], [20] has been widely applied in in animation and computer graphics as a parametric curve. Under the given points $P_0, P_1, \ldots, P_n$, the n-th-order Bézier curve can be expressed as [14]:

$$B(t) = \sum_{i=0}^{n} \binom{n}{i} P_i (1-t)^{n-i} t^i \quad t \in [0, 1] \tag{1}$$

where $B(t)$ are the coordinates of the points on the curve; $t \in [0, 1]$ is an auxiliary parameter; P_i are the control points that determine the shape of the curve; n is the number of control points; *n-1* is the order of the curve; $\binom{n}{i} = \frac{n!}{i!(n-i)!}$ is the binomial expansion.

In a 2D Cartesian Coordinate System, the longitudinal displacement x and lateral displacement y are both expressed as functions of parameter t. Let $P_i = (x_i, y_i)$, $i = 0, 1, 2, 3, 4, 5$ be the control points. Then, the n-th-order Bézier curve can be described as:

$$\begin{cases} x = \sum_{i=0}^{n} \frac{n!}{i!\,(n-i)!} x_i (1-t)^{n-i} t^i \\ y = \sum_{i=0}^{n} \frac{n!}{i!\,(n-i)!} y_i (1-t)^{n-i} t^i \end{cases} \tag{2}$$

where (x_i, y_i) are the coordinates of the control points.

The curvature of the Bézier curve, $K_{(t)}$, can be calculated by [14], [15]:

$$K_{(t)} = \frac{x'y'' - y'x''}{(x'^2 + y'^2)^{\frac{3}{2}}} \tag{3}$$

where $x' = \frac{dx}{dt}$; $x'' = \frac{dx'}{dt}$; $y' = \frac{dy}{dt}$; $y'' = \frac{dy'}{dt}$.

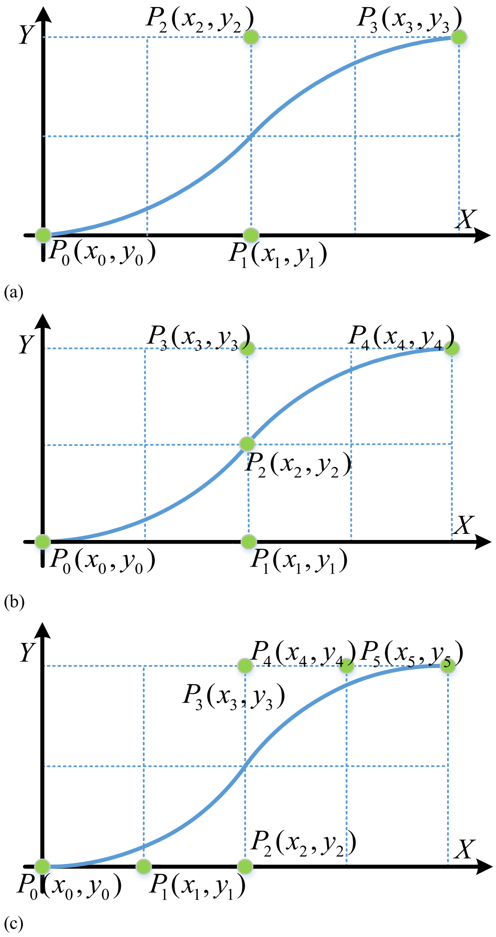

FIGURE 1. Example paths based on third-, fourth- and fifth-order Bézier curves.

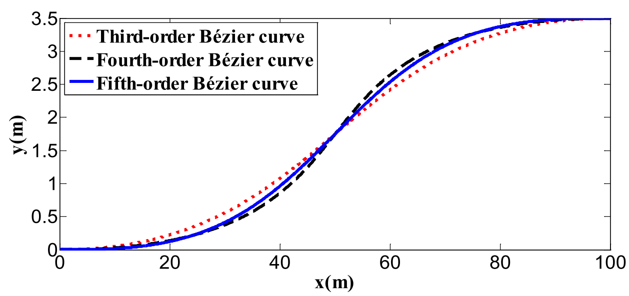

FIGURE 2. The paths based on third, fourth and fifth order Bézier curves.

The paths based on third-, fourth- and fifth-order Bézier curves are presented in Figure 1 below.

Before analysing the curve features in different orders, it is assumed that the lateral displacement of lane change equals the lane width $y_d = 3.5$m; the longitudinal displacement of lane change equals the driving distance $x = 100$m through the lane change time $t_{lc} = 5$s at the constant vehicle velocity $v_x = 20$m/s. Next, the lane change paths planned by third-, fourth- and fifth-order Bézier curves were simulated on Matlab (Figures 2-3).

As shown in Figures 2, the paths based on third and fourth order curves were smooth between the start and the

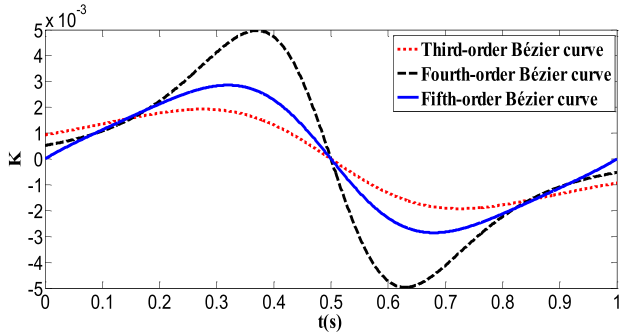

FIGURE 3. The curvature of the paths based on third, fourth and fifth order Bézier curves.

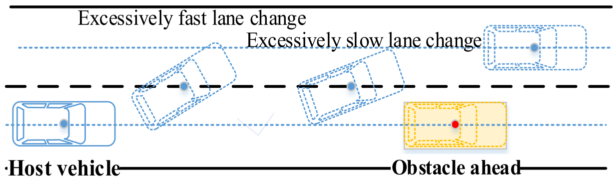

FIGURE 4. The consequences of excessively fast or slow lane change.

destination, but the curvatures at the two ends were nonzero (Figure 3), making it impossible for the vehicle to track the paths in actual environment. Despite being less curved at the two ends, the path based on the fourth-order curve had a much greater maximum curvature than that based on the third-order one. Unlike these two paths, the path based on the fifth-order curve had zero curvatures at both ends. Under the same conditions, the path based on the fifth-order curve had a slightly larger maximum curvature than the third-order curve, yet the curvature was still far smaller than the curvature at the lateral acceleration of 0.2g m/s^2, where g is the acceleration of gravity.

Since the lane change path must have zero curvature at both ends, the fifth-order Bézier curve was adopted to plan the path. Considering that the path shape may vary with the control points, the path planning based on the fifth-order Bézier curve was simplified into the search for six optimal control points, aiming to achieve dynamic planning of lane change path to avoid colliding into a front vehicle.

III. COLLISION-FREE PATH PLANNING BASED ON FIFTH-ORDER BÉZIER CURVE

The vehicle velocity directly affects the safety and comfort of lane change. As shown in Figure 4, the vehicle may turn over if the lane change occurs too fast (e.g. the maximum lateral acceleration exceeds the safety threshold). If the lane change occurs too slowly, the driver may feel quite comfortable, but the vehicle faces the risk of colliding into the obstacle.

A. BOUNDARY SETTING

Firstly, a coordinate system was established with the centroid and the driving direction of the host vehicle as the origin and x direction, respectively; the y direction was set as the left vertical line of the x direction. Both the host vehicle and the front vehicle were assumed as circles, with a radius just enough to cover all boundaries (Figure 5).

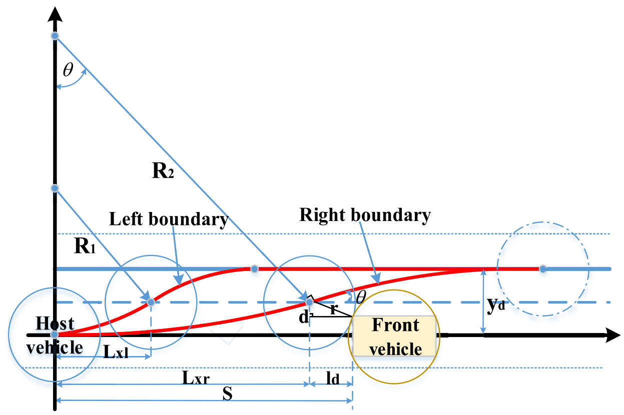

FIGURE 5. The path boundaries for lane change.

1) PERFORMANCE BOUNDARY OF THE HOST VEHICLE

According to the lateral acceleration constraint for emergency lane change [5], the path planning was conducted at the maximum lateral acceleration $a_{y1} = 0.2\text{gm/s}^2$. Then, the arc radius of the left boundary can be computed by:

$$a_{y1} = \frac{v_x^2}{R_1} \tag{4}$$

As shown in Figure 5 (left boundary), the performance boundary encompasses two arcs with the radius R_1. The upper and lower arcs are symmetric about the path centre.

2) BOUNDARY WITH A FRONT VEHICLE

Taking the front vehicle into account, the contact point of the two circles was considered as a control point of the lane change path. Then, the lower part of the right boundary was determined as the arc linking up the start point and the centre of the host vehicle. The upper part of the right boundary was plotted based on its symmetry with the lower part about the path centre (Figure 5, right boundary).

Drawing on References [21]–[24], the safe distance for the host vehicle to achieve collision-free lane change can be simplified as $S = (2-3)v_x$. From equations (5)-(7), the relevant parameters of the right boundary can be expressed as:

$$a_{y2} = \frac{v_x^2}{R_2} \tag{5}$$

$$R_2^2 = L_{xr}^2 + (R_2 - \frac{y_d}{2})^2 \tag{6}$$

$$\begin{cases} l_d^2 = r^2 - d^2 \\ r = \sqrt{(\frac{B}{2})^2 + (\frac{L}{2})^2} \\ d = \frac{1}{2}(y_d - B) \end{cases} \tag{7}$$

where a_{y2} is the minimum lateral acceleration to achieve collision-free lane change with a front vehicle; v_x is the speed of the host vehicle; y_d is the lane width; L_{xr} is the longitudinal distance from the start point to the centre of the host vehicle; l_d is the longitudinal distance from the centre of the host vehicle to the contact point; R_2 is the arc radius of right boundary;r is the radius of the circle for the host vehicle; B and L are the width and length of the vehicle, respectively; d is the distance from the edge of the host vehicle to that of the lane. All these parameters are diagrammed in Figure 5. The sum of L_{xr} and l_d equals the safe distance for the host vehicle to achieve collision-free lane change.

B. MODELING AND OPTIMIZATION OF PATH PLANNING

The following assumptions were put forward to ensure that the feasibility of the planned path and the smooth operation of the host vehicle in lane change: (1) The two ends of the path must be of zero curvature if the lane change takes place on a straight road; (2) The path should be continuous in curvature; (3) The maximum swing angle of the vehicle in lane change should be minimized; (4) The maximum curvature, i.e. the turning radius, and the maximum lateral acceleration should be minimized, aiming to ensure the driving comfort in lane change; (5) The lane change distance should be long enough to prevent collision with the surrounding vehicles.

Under the above assumptions, the multi-objective function can be established as:

$$\min F = \omega_1 K_0 + \omega_2 K_{\max} + \omega_3 \theta + \omega_4 t_{lc} \tag{8}$$

where, ω_i, $i = 1, 2, 3, 4$ is the weight coefficient; K_0 is the curvature at the start point, i.e. the curvature $K_{t=0}$ at t $= 0$; $0 < \theta < 45^\circ$ is the swing angle [14]; K_{max} is the maximum curvature in lane change, which reflects the maximum lateral acceleration; t_{lc} is the lane change time. Since the curvature is zero at t $= 0.5$, the θ can be regarded as the path slope at that moment $\left.\frac{dy}{dx}\right|_{t=0.5}$.

The slope of the path at any point can be expressed as:

$$\frac{dy}{dx} = \frac{dy}{dt}\frac{dt}{dx} \tag{9}$$

According to Equations (2), (3) and (9), both the curvature and the slope of the path at any point (K and dy/dx) can be illustrated as a function of auxiliary parameter t and undetermined variables x_1 and x_2. Thus, the path planning can be simplified as the search for the optimal values of undetermined variables under constraints.

Then, the multi-objective function and its constraints can be respectively converted into:

$$\min F = \omega_1 K_{t=0} + \omega_2 K_{\max} + \omega_3 \left.\frac{dy}{dx}\right|_{t=0.5} + \omega_4 t_{lc} \tag{10}$$

$$\begin{cases} K_{\max} \le \dfrac{a_{y\max}}{v_x^2} \\ \tan 0^\circ < \left.\dfrac{dy}{dx}\right|_{t=0.5} < \tan 45^\circ \\ 0 < x_1 < x_2 \\ L_{xl} < x_2 < L_{xr} \end{cases} \tag{11}$$

where a_{ymax} is the maximum lateral acceleration for lane change; L_{xl} and L_{xr} are the longitudinal distances from the start point to the midpoints of left and right boundaries, respectively; v_x is the velocity of the host vehicle. The variation of v_x induces changes to the boundary values, resulting in different paths. In order to facilitate the explanation of the proposed method, the value of weight coefficients was set as $\omega_1 = \omega_2 = \omega_3 = \omega_4 = 1$, which represent that the vehicle performance and driving comfort are of equal importance.

Since the curvatures are zero at both ends of the path based on the fifth-order Bézier curve, the six optimal control points can be determined as follows. Firstly, the start point (x_0, y_0) of the path was taken as the origin, i.e. $x_0 = 0$ and $y_0 = 0$, and x_1 and x_2 were set as undetermined variables. In the light

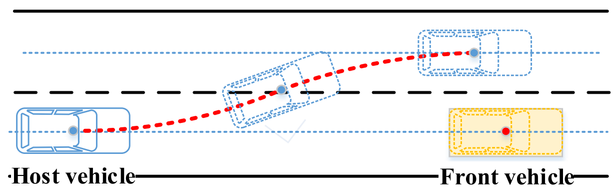

FIGURE 6. Simulation scenario (Blue: The host vehicle; Orange: The front vehicle).

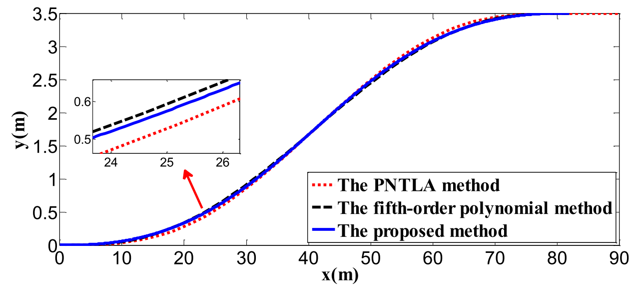

FIGURE 7. The paths based on the three methods.

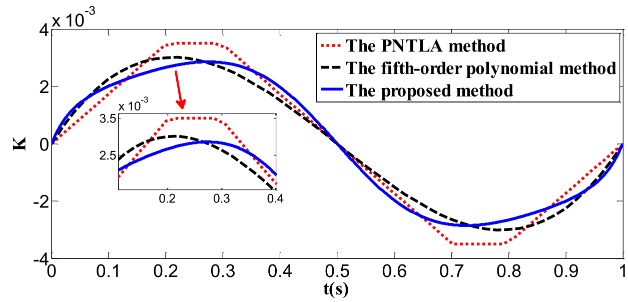

FIGURE 8. The path curvatures based on the three methods.

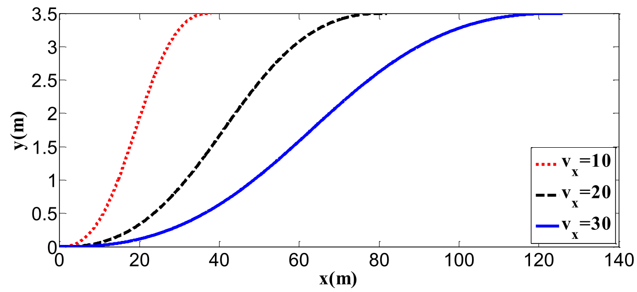

FIGURE 9. The paths at different velocities.

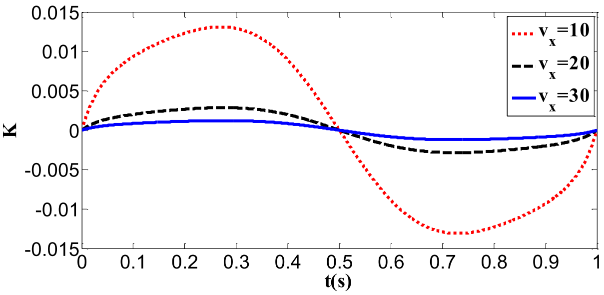

FIGURE 10. The curvatures at different velocities.

of the symmetry of the path, the coordinates of the control points can be derived as $x_3 = x_2, x_4 = x_2+x_2-x_1, x_5 = 2x_2$, $y_0 = y_1 = y_2 = 0$, and $y_3 = y_4 = y_5 = y_d$, respectively, where $y_d = 3.5$m.

The values of x_1 and x_2 can optimized based on the objective function at different vehicle velocities, yielding the coordinates of the six points. In this way, an ideal path can be obtained based on the fifth-order Bézier curve, considering the front vehicle and boundary constraints.

IV. SIMULATION VERIFICATION

The proposed path planning method was verified through simulation with a front vehicle (Figure 6). The parameters were set as: $a_{ymax} = 0.2\text{gm}/s^2$, $\omega_i = 1$, $y_d = 3.5$m, $B = 3$m, $L = 4$m and $S = 3v_x$.

A. SIMULATION WITH DIFFERENT ALGORITHMS

The proposed method was compared with the PNTLA method [5] and the fifth-order polynomial method [11] through Matlab simulation at $v_x = 20$m/s and $t_{lc} = 4.1s$.

It can be seen from Figures 7-8 that, all three methods outputted lane change paths with zero curvature at both ends. The maximum curvature (3.4×10^{-3}) of the PNTLA method was much greater than those of the other two methods, which suppresses driving comfort. Both the fifth-order polynomial method and the proposed method generated smooth paths. However, the maximum curvature (3.1×10^{-3}) of the former was higher than that (2.8×10^{-3}) of our method. In addition, the fifth-order polynomial method only works when the destination is known in advance, while the proposed method does not require the prior knowledge of the destination.

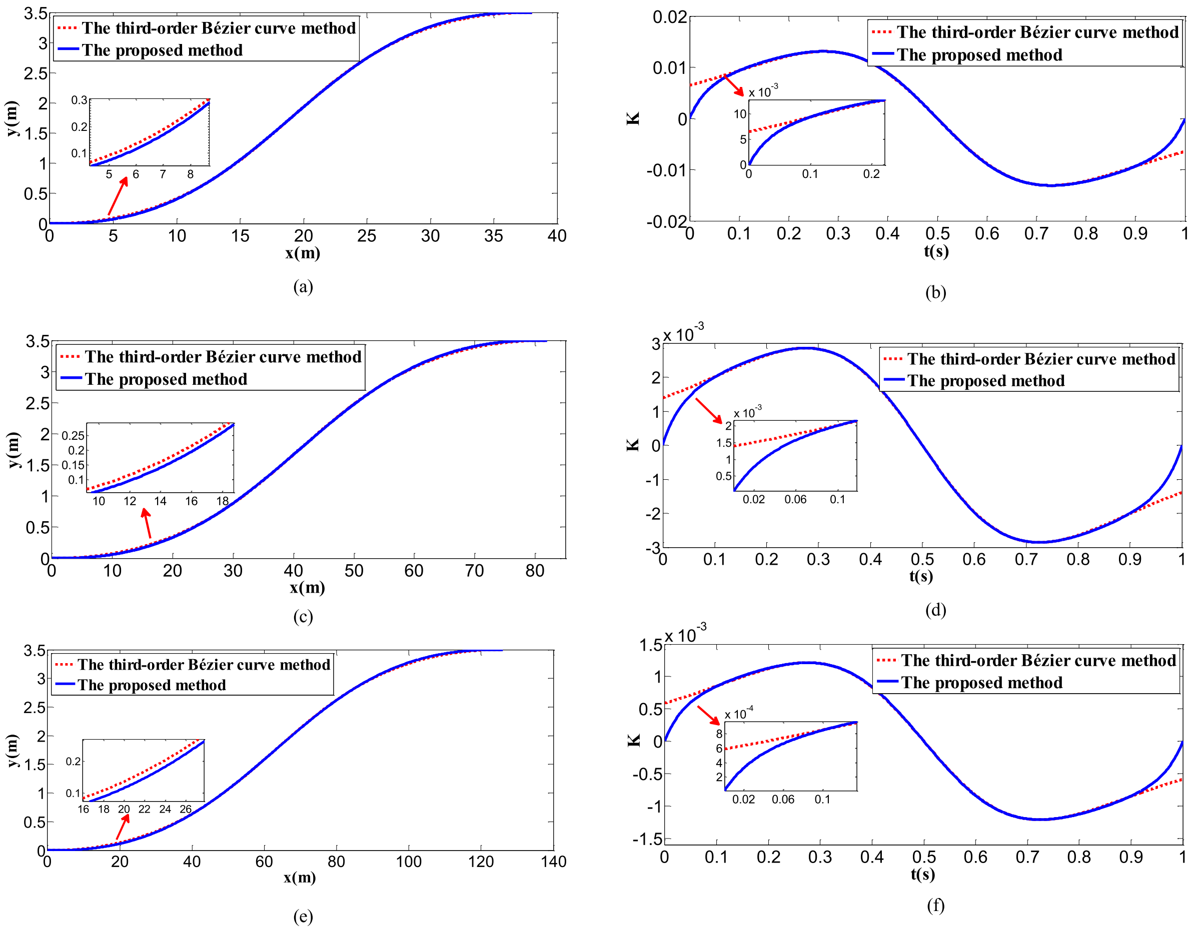

FIGURE 11. The paths (a, c, e) and curvatures (b, d, f) at different velocities.

TABLE 1. Comparison between the third-order Bézier curve method and the proposed method.

Vehicle velocity (m/s)	Order	$K_0\,(10^{-3})$	Permissible maximum curvature $K_{max\_permissible}$ (10^{-3})	Actual maximum curvature K_{max_fact} (10^{-3})	Maximum swing Angle $\omega(°)$	Lane change distance $S_{lc}(m)$	Lane change time $t_{lc}(S)$
v_x=10 (low)	3rd	6.45	19.6	13.09	28.93	39	3.9
	5th	0		13.07	10.26		
v_x=20 (medium)	3rd	1.38	4.9	2.86	14.36	82	4.1
	5th	0		2.85	4.81		
v_x=30 (high)	3rd	0.59	2.2	1.22	9.46	126	4.2
	5th	0		1.21	3.13		

B. SIMULATION AT DIFFERENT VELOCITIES

The proposed method was further simulated at three typical velocities: the low velocity $v_x = 10m/s$ for urban traffic, the medium velocity $v_x = 20m/s$ for general traffic and the high velocity $v_x = 30m/s$ for expressway traffic. The simulated paths and curvatures are presented in Figures 9 and 10 below.

The simulation results show that the minimum safe distance between the host vehicle and the front vehicle for collision-free lane change was 39m at $v_x = 10m/s$, 82m at $v_x = 20m/s$ and 126m at $v_x = 30m/s$. The maximum lateral acceleration of the planned path was 13.1×10^{-3} at $v_x = 10m/s$, 2.85×10^{-3} at $v_x = 20m/s$ and 1.21×10^{-3} at $v_x = 30m/s$, all of which are much smaller than the maximum curvature. These results prove that our method performs well at different vehicle velocities and outputs lane change paths that perfectly balance vehicle performance and driving comfort.

Furthermore, our method was contrasted with the third-order Bézier curve method at the above three vehicle velocities through Matlab simulation. The simulated results are displayed in Figure 11 and Table 1 below.

It can be seen from Figure 11 and Table 1 that our method outperformed the third-order Bézier curve method at all three velocities, whether in the curvature at the start point, the maximum curvature and the swing angle, and outputted the lane change path dynamically with a vehicle ahead. The simulated results also show that the path generated by our method had zero curvature at both ends, and a smooth shape with no catastrophe point. To sum up, our method is a desirable tool for creating a collision-free path for lane change.

V. CONCLUSION

After comparing various path planning methods for lane change, this paper develops a path planning method based on fifth-order Bézier curve for lane change with a vehicle in front and several boundary constraints. Specifically, multi-objective optimization function was set up, considering the curvature at the start point, the maximum curvature, the maximum swing angle, and the lane change time. Next, the coordinates of the control points that determine the curve shape were solved, and thus the path was set up. On this basis, the optimal path was planned for the lane change before collision avoidance. Simulation results show that our method works well at different vehicle velocities and provides a desirable tool to plan a dynamic path in actual traffic environment.

The main contribution of this research lies in the fact that our path planning method does not require the prior knowledge of the destination to generate a curvature-continuous lane change path without any catastrophe point, which is more in line with the actual conditions. This unique property provides a guarantee to the collision-free lane change of the host vehicle. Thus, our method has a great application potential.

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