Prediction Model and Simulation Analysis of the Speed of the Curve Based on the Cooperation of People and Vehicle

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Abstract—Curve is the accident road section, reducing the speed of vehicles in curve is an effective measure to reduce traffic accidents. How to predict the speed of vehicles in the safe curve is the basis of vehicle active control. In this paper, the vehicle dynamics model and the curve speed prediction model based on the cooperation of people and vehicles are established. Based on this model, the simulation analysis of the curve speed prediction is carried out, and the safe speed of the vehicle under different loading mass and road adhesion coefficient is obtained. (Abstract)

1. INTRODUCTION
There is a high probability and severity of traffic accidents in curve sections. The speed of the vehicle is too fast in the curve, which leads to the side slip and rollover of the vehicle. It is of great significance to study the safe speed of vehicle in curve and provide the safety of vehicle in curve \cite{1-2}. Many scholars at home and abroad have also done a lot of research on safe driving in curves. Liu Yang et al. Studied the safe speed threshold of vehicles in curves under the action of crosswind by establishing simulation model\cite{3}. Xu Jin et al. Established a prediction model of vehicle speed considering the influence of curve geometry and traffic volume\cite{4}. Tang Geteng et al. Used the software of trucksim to establish the dynamic model of the whole vehicle, carried out the orthogonal simulation experiments of different curve radius and passing speed, and obtained the safe speed threshold under different curve radius \cite{5}. Sun Chuan \cite{6} et al. Introduced vehicle structural parameters and driver's characteristics into the traditional calculation model of safe speed in curve, analyzed and compared the speed changes of a truck under different working conditions.

2. MODELS
2.1. 7-DOF vehicle dynamics model
The 7-DOF dynamic model of heavy vehicle is established as shown in Figure 1. The model includes the longitudinal, lateral and yaw motion of the vehicle, as well as the rotational motion of four wheels.

The origin of the coordinate system is located at the center of mass of the vehicle; the longitudinal axis of symmetry of the vehicle is the axis, the lateral axis of symmetry is the axis, and passes through...
the center of mass of the vehicle. The positive direction of each quantity is the direction marked in the figure.

![Figure 1 7-DOF dynamic model of heavy vehicle](image)

Based on the model shown in Figure 1, the dynamic equation of heavy vehicle can be obtained.

**Dynamic equation of longitudinal motion**

\[
\dot{v}_x = a_x + r \cdot v_y
\]

\[
\delta_x = i \cdot \delta
\]

\[
a_x = \frac{1}{m} \left[ (F_{1x} + F_{12}) \cos(\delta) - (F_{2x} + F_{2y}) \sin(\delta) + F_{3x} + F_{4x} \right]
\]

**Dynamic equation of lateral motion**

\[
\dot{v}_y = a_y - r \cdot v_x
\]

\[
a_y = \frac{1}{m} \left[ (F_{1x} + F_{12}) \sin(\delta) + (F_{2x} + F_{2y}) \cos(\delta) + F_{3y} + F_{4y} \right]
\]

**Dynamic equation of yaw motion**

\[
\dot{r} = \frac{1}{I_x} \left[ a(F_{1x} + F_{12}) \sin(\delta) + a(F_{2x} + F_{2y}) \cos(\delta) - b(F_{3y} + F_{4y}) \right]
\]

\[
-\frac{d_1}{2} \left( F_{1x} - F_{12} \right) \cdot \cos(\delta) + \frac{d_1}{2} \left( F_{2x} + F_{2y} \right) \cdot \sin(\delta) - \frac{d_2}{2} \left( F_{3x} - F_{4x} \right)
\]

The specific meanings and units in the model are shown as follows.

- \( m \) Whole vehicle Quality kg
- \( m_s \) Spring Load Quality kg
- \( u \) Longitudinal speed m/s
- \( \beta \) Sideslip Angle rad
- \( \omega_r \) Yaw rate rad/s
- \( \alpha_f, \alpha_r \) Front and rear tyre sideslip angle
- \( I_x, I_z \) Moment of inertia around the x, z axis kg \cdot m^2
- \( \phi \) Vehicle roll angle rad
- \( \phi' \) Vehicle roll rate rad/s
- \( \phi'' \) Vehicle roll acceleration rad/s^2
- \( a, b \) The distance between the centroid and the front and rear axes m
- \( K \phi \) Total lateral roll stiffness of front and rear suspension N \cdot m/rad
- \( k_f, k_r \) Front and rear tire side deflection stiffness N/rad
- \( C \phi \) Total lateral tilt damping of front and rear suspension N \cdot m \cdot s/rad
- \( \omega r' \) Vehicle yaw rate acceleration rad/s^2
2.2. Tire model

The Dug off tire model is selected as the tire model, and the longitudinal and lateral forces acting on each wheel can be expressed as follows

\[ F_x = \mu \cdot F_z \cdot C_x \cdot \frac{\lambda}{1 - \lambda} \cdot f(L) \]  

\[ F_y = \mu \cdot F_z \cdot C_y \cdot \frac{\tan(\alpha)}{1 - \lambda} \cdot f(L) \]  

\[ f(L) = \begin{cases} 
L \cdot (2 - L), & L < 1 \\
1, & L \geq 1 
\end{cases} \]  

\[ L = \frac{1}{2\sqrt{C_x^2 \cdot \lambda^2 + C_y^2 \cdot \tan^2 \alpha}} \cdot (1 - \lambda) \]  

\[ (1 - \varepsilon \cdot v_i \cdot \sqrt{C_x^2 \cdot \lambda^2 + C_y^2 \cdot \tan^2 \alpha}) \]  

In the formula, \( \lambda \) indicates the longitudinal slip rate of the tire, \( C_x \) indicates the sideslip stiffness of the tire, \( C_y \) indicates the longitudinal stiffness of the tire, \( \alpha \) indicates the sideslip angle of the tire, \( \mu \) indicates the adhesion coefficient of the road, and \( \varepsilon \) indicates the speed influence coefficient. It is a parameter related to the tire structure and material, which can modify the influence of the wheel slip speed on the tire force.

Using the Dug off tire model, the forces on the wheels of the car are obtained. Figure 2 shows the rotating forces on the driving wheels, and figure 3 shows the rotating forces on the driven wheels.

![Figure 2 Schematic diagram of driving wheel rotation force](image)

![Figure 3 Schematic diagram of driven wheel rotation force](image)
According to the force analysis, the dynamic equation of driving wheel rotation is as follows:

$$I_{o} \cdot \dot{\omega} = T_{d} - R_{o} \cdot F_{x} - T_{b}$$  \hspace{1cm} (11)$$

The dynamic equation of driven wheel rotation is:

$$I_{o} \cdot \dot{\omega} = -R_{o} \cdot F_{x} - T_{b}$$  \hspace{1cm} (12)$$

In the above formula, $T_{d}$ indicates the wheel driving torque and $T_{b}$ indicates the wheel braking torque.

3. THE PREDICTION MODEL OF THE SPEED OF THE CURVE.

Based on vehicle dynamics, the critical speed of vehicle in curve is the limit speed in general. The road traffic system is a complex large system, which is affected by drivers, vehicles, roads and environment. Therefore, based on the critical speed model of vehicle dynamics, the safety factor $K$ is introduced. It reflects the static comprehensive factors of vehicle driving safety, so as to realize the cooperation and coupling of static and dynamic factors of vehicle driving safety. The safety factor $K$ is calculated as follows:

$$k = \sqrt{\frac{y}{75}}$$  \hspace{1cm} (13)$$

Where $y$ is the weighted sum of the quantitative values of the influencing factors such as driver, vehicle, road and curve environment. In addition, considering that when the vehicle is subjected to the lateral force, the elastic deformation of the outer tire will occur, so that the ground center of the tire will shift inward, and the track width will decrease, which will reduce the safety critical speed by about 5%. Therefore, the correction coefficient $K$ of the sideslip characteristics of the tire is introduced, $K$ is taken as 0.95.

From the above-mentioned dynamic model, we can get the critical speed model of vehicle driving in the curve as follows:

$$v = \min\left( v_{\text{max}}, v_{\text{min}} \right) = \min\left( \frac{\phi_{o} + \theta_{e} \cdot R_{g}}{1 - \theta_{e} \cdot R_{g}} \cdot \sqrt{\frac{t + 2H_{e} \theta_{b} \cdot R_{g}}{2H_{e} + t \theta_{b} \cdot R_{g}}} \right)$$  \hspace{1cm} (14)$$

Combining formula (13), formula (14) and the correction coefficient $K$ of tire cornering characteristics, the prediction model of safe vehicle speed in the curve based on the cooperation of people and vehicle is as follows:

$$v = \min\left( v_{\text{max}}, v_{\text{min}} \right) = \min\left( K \cdot \frac{\phi_{o} + \theta_{e} \cdot R_{g}}{1 - \theta_{e} \cdot R_{g}} \cdot \sqrt{\frac{y}{75}}, K \cdot \frac{\theta_{b} \cdot R_{g}}{t \theta_{b} \cdot R_{g}} \cdot \sqrt{\frac{y}{75}} \right)$$  \hspace{1cm} (15)$$

4. PREDICTION AND ANALYSIS OF SAFE SPEED IN CURVE

According to the simulation of the speed of the selected vehicle passing the curve in the experimental section, the safe speed threshold of the vehicle passing the curve section under the influence of different loading mass and different road adhesion coefficient is obtained, and the three-dimensional curved surface of the safe speed threshold of the vehicle in the curve section affected by various factors is obtained, as shown in Figure 4. The least square method is used to fit the safety vehicle speed threshold under the influence of this factor, as shown in Figure 5. When the road adhesion coefficient is within the range of 0.6-1.0, the safety vehicle speed threshold of vehicles with different loading masses passing through the curve is basically unchanged. Therefore, the adhesion coefficient 0.6-1.0 is used as an interval for fitting again, and the fitting results are shown in Figure 6. The safe vehicle speed threshold of the selected curve section can be obtained under the influence of different loading mass and road adhesion coefficient.
5. CONCLUSIONS
The prediction model of the safe speed of the vehicle in the curve is established, and the simulation analysis of the prediction of the safe speed is carried out by using the established model. The safe speed of the vehicle in the curve is obtained under different loading mass and road adhesion coefficient. This study can provide theoretical guidance for the active control of the traffic on the curve.

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REFERENCES
[1] SUN C, WU C Z, ZHU D F, et al. Improved model study of safety speed calculation in curves [J]. Chinese Journal of Highway and Transport, 2015, 25(8): 101-108.
[2] XU M, HUANG X, ZHANG C, et al. Application of fuzzy synthesis evaluation to driving safety analysis of sharp curves on mountain expressways[J]. China Journal of Highway and Transport, 2016, 29(6):186-197.

[3] LIU Y, YU R D, SONG L X. Simulation study on safe travel speed threshold of curve lane under crosswinds[J]. Journal of Guangxi University (Natural Science Edition), 2016, 41(2):506-511.

[4] XU J, LUO Q, MAO J C, et al. Speed prediction model of car/truck considering the effect of curve geometric features and traffic volume[J]. China Journal of Highway and Transport, 2012, 25(5):47-57.

[5] TANG G T, REN C X, LI C. A determination method of safety driving speeds on different radii based on Trucksim[J]. Journal of Highway and Transportation on Research and Development, 2016, 33(6):134-139.

[6] SUN C, WU C Z, ZHU D F, et al. Improved model study of safety speed calculation in curves[J]. Chinese Journal of Highway and Transport, 2015, 25(8):101-108.