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Research on Road Safety Evaluation in Curves Based on TruckSim-Simulink Co-simulation

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Abstract: Highway curve is prone sections accidents, this paper studies the curve road traffic safety situation based traffic safety evaluation in curves, and it uses the vehicle lateral stability to analyze curve road traffic safety features. It discusses TruckSim and Simulink co-simulation problems and establishes TruckSim vehicle simulation model, Vehicle simulation model is established in TruckSim, though the evaluation is designed in Simulink. Geometry radius curve indicators of the current specification limit road for alignment design is analyzed and verifies the reasonableness by co-simulation. The simulation results show that it is very beneficial to use a larger bend radius for road safety under conditions permit. Drivers only need to slightly adjust the steering angle so that the vehicle can pass the curve sections in larger bend radius, it not only reduces the driver's driving strength, but also avoids the risk of vehicle skidding or roll. The results provide a reference for future vehicle safety and road safety designs.

1. Introduction

Compared to the straight road section, highway bend road section usually becomes the section with frequent occurrence of traffic accidents due to the characteristics of its geometric line. According to the statistics of the MPS, it reveals that the national road traffic accidents in 2012 caused 59997 casualties. Though the accidents happening at bend road section only account for 7.86% of total traffic accidents, the fatality at bend road section accounts for 16.8% of the total fatalities [1]. It thus could be found that the severity of bend accidents is generally very high. To improve the traffic safety situation of bend road section, it is significantly meaningful to study the driving safety of vehicles at the bend road section [4][5]. According to the problems about driving safety at the bend road section, the scholars at home and abroad have already carried out research from many perspectives. In particularity, by beginning with the influence factors (people, vehicles, road and environment) of driving safety at the bend road section, the qualitative relations among influence factors and the driving safety at the bend road section was analyzed. The scholars including KharagPur et al [6] analyzed some important parameters of the bend road by dividing the bend road into independent units and studying the linear design of the road. Meanwhile, some other scholars such as Dabbour [7] proposed the method of evaluating the safety of bend road section based on parabola principle in mathematical model. The professors like Xiao et al [8] from Beijing Institute of Technology studied the relationship between
bend road curve change and safety feeling of the driver based on simulation analysis by adopting subjective evaluation method and introducing the subjective feeling of the driver into bend road safety evaluation. Meanwhile You et al [9] from Southeast University built three-degree-of-freedom kinetic model through MATLAB/Simulink to study the influences of geometric parameters of bend road on vehicle stability.

Driving safety evaluation is always regarded as the research hotspot in the field of road traffic safety. The evaluation on driving safety at bend road section is mainly studied mainly through the lateral stability of the vehicle [10]. The lateral stability of the vehicle indicates the limiting performance of side slip or turn doesn’t occur during the driving of the vehicle. It is an important factor influencing the driving safety. Its main research content includes study on influence factors of lateral stability, study on evaluation methods and evaluation index research, etc.

The characteristic of the driving safety at bend road section are analyzed based on lateral stability of vehicle according to the evaluation problem of the driving safety features at the bend road section. Through united simulation experiment of TruckSim-Simulink, vehicle kinetics model is built in TruckSim. In addition, evaluation indexes are designed for driving safety at bend road section to analyze the quantitative relationship between limiting valuation of road curve radius and driving safety at bend road section. There is a definite guiding significance in studying the influences of lateral stability of vehicle on driving safety at the bend road section to improve the safety design of vehicle and road.

2. Road Accident Characteristic on Curves

Through analysis of first three types of accident occurring at sharp bend road section occurring nationwide from 2010 to 2012 with the average highest proportion [1][2][3], it could be found that the average proportion of accidents including rollover, head-on collision and car fall, into the bend road accidents reaches 22.7%, 29% and 12.4% respectively. The turnover is caused mainly due to the high speed of the vehicle when driving into the bend road section. Thus, the centrifugal force of the vehicle is too large and overturning moment of the vehicle reaches the threshold value. Finally, the sideslip and rollover of the vehicle is caused. As for the head-on collision, the driving track of at least one vehicle of two driving on the road deviates from the expected one of the driver. The driving track of the two vehicles crosses at the bend road section. Further, the high driving speed of the vehicle is also one of main reasons for the crossing of the track. Car fall is generally caused by side slip and turn during the driving of the vehicle. Therefore, the sideslip and rollover of the vehicle caused by the irrational driving speed is the main reason for causing the traffic accidents at bend road, which has great influence on driving safety of the bend road section.

3. Evaluation Index of Driving Safety on Curves

Lateral stability of vehicle has significant influence on driving safety at bend road section. The driving safety of vehicle at bend road section can be accurately analyzed by evaluating the lateral stability of the vehicle at bend road section. Given a lot of indexes evaluating the lateral stability of the vehicle, the phenomenon of side slip and turn of vehicle is mainly analyzed according to the morphological characteristics of accidents at bend road section. For this regard, the two indexes sideslip and rollover are designed to evaluate the driving safety at bend road section.

3.1. Evaluation Index of Sideslip

When the vehicle drives at the bend road section, it is necessary to provide the driving or braking force of the vehicle along the longitudinal direction of the vehicle and the lateral force along the lateral direction for the adhesion force of the pavement, shown as in the formula (1):

\[(mg\mu)^2 = F_x^2 + F_y^2\]  

\[\text{(1)}\]

In which: \(m\) indicates the quality of the vehicle, \(\mu\) road adhesion coefficient, \(F_x\) the driving or braking force along the longitudinal direction of the vehicle and \(F_y\) lateral force of the vehicle.
From the formula (1), it could be obtained that the increase of lateral or longitudinal force of the vehicle will inevitably result into the decrease of the other. Therefore, when the vehicle driving at the bend road, the resulting force of the longitudinal and lateral force exceeds the maximum adhesive force between the tire and road surface, the side slip of the vehicle will be caused, in which the lateral force $F_y$ of the vehicle is as shown in the formula (2) [11].

$$F_y = ma_y$$

$$a_y = \frac{V^2}{R}$$

In which: $R$ indicates the road circle curve radius, $V$ the speed when the vehicle drives into the bend road and $a_y$ the lateral acceleration of the vehicle.

Through analysis, it could be reckoned that when the vehicle drives into the bend road, if the lateral acceleration is too high, it is necessary to provide corresponding lateral force for the road surface to prevent from the side slip of the vehicle. Therefore, the lateral stability of the vehicle is controlled by limiting the lateral acceleration on the vehicle. According to the national standard, it regulates that the lateral acceleration of the heavy-duty vehicle should not exceed 0.3g while that of the common vehicles cannot exceed 0.4g to ensure the lateral stability of the vehicle when driving into the bend road or turning. Therefore, it is necessary to use lateral acceleration as the index to evaluate the lateral stability, analyze the lateral stability of the vehicle and evaluate the driving safety of the vehicle at bend road section.

### 3.2. Evaluation Index of Rollover

According to the research, it indicates that it is highly reliable to use transfer rate of lateral load ($LTR$ value) as the side slip index of the vehicle [12]. To better measure the influence factors of side slip risk of the vehicle, the lateral stability of the vehicle is analyzed with improved $LTR$ index $LTR_{\text{New}}$, namely represented by the quadratic integral average of absolute value of transfer rate of load transfer of the tire within the unit time. Its physical significance is average power [13]. As for side slip risk measurement index, it is as shown in the formula (4) and (5) [14].

$$LTR = \left| \frac{\sum_{i=1}^{n} (F_{li} - F_{ri})}{\sum_{i=1}^{n} (F_{li} + F_{ri})} \right|$$

$$LTR_{\text{New}} = \int_{t_1}^{t_2} |LTR| dt / (t_2 - t_1)$$

In which: $F_{li}$ indicates the vertical load on the left wheel of the vehicle, $F_{ri}$ the vertical load on the right wheel of the vehicle, $i$ and $n$ the location of axle and the total number of axles, $t_1$ the previous time, $t_2$ the later time. For the absolute value of $LTR$ is between [0, 1], it is 0 when the vehicle is at good condition and 1 when the vehicle is at limited condition. In analysis on lateral stability of vehicle, $LTR_{\text{New}}$ is usually used as the evaluation index judging whether the side slip of the vehicle will occur. When $0.8 \leq LTR_{\text{New}} \leq 1$, the vehicle is at unstable state and the side slip danger can be easily caused; when $0.6 \leq LTR_{\text{New}} \leq 0.8$, there is certain hidden safety danger in the vehicle. When $LTR_{\text{New}} \leq 0.6$, the vehicle is at safety state. Therefore, the side slip stability of vehicle is analyzed by using $LTR_{\text{New}}$ as the index evaluating the side slip stability to further evaluate the driving safety at bend road section.

### 4. Vehicle-road Coupled Model on Curves

#### 4.1. Vehicle Model

As shown in the Figure 1 (a), modeling of the commercial vehicle is completed by inputting its kinetic parameters to evaluate the driving safety at the bend road section through simulation of lateral stability of the vehicle. As shown in the Figure 2 (b), simulation vehicle is the four-wheel commercial vehicle model. Its main parameters are as shown in the Table 1.
Fig. 1 Vehicle Simulation Model

(a)                                   (b)

Table 1 Main Parameters of Vehicle Model

| Parameter                          | Value | Parameter                          | Value |
|------------------------------------|-------|------------------------------------|-------|
| Sprung Mass /kg                    | 4457  | Rotational Inertia $I_x$ / kg·mm²   | 250   |
| Height of Center of Mass /mm       | 1750  | Rotational Inertia $I_y$ / kg·mm²   | 6250  |
| Wheel Span /mm                     | 1863  | Rotational Inertia $I_z$ / kg·mm²   | 6250  |
| Tire Size /mm                      | 510   | Aspect Ratio                       | 1.40  |

4.2. Road Model on Curves

When selecting the circle curve radius for the bend road section of highways at all levels, it is necessary to meet the design speed of the road to ensure the driving safety of the vehicle at the bend road section [15]. The minimum radius [16] of road circle curve regulated by the national standard is as shown in the Table 2.

Table 2 Minimum Radius of Horizontal Curves

| Minimum Radius of Circle Curve (m) | Typical Value | Limit Value |
|------------------------------------|---------------|-------------|
|                                    | 1000 | 700 | 400 | 200 | 100 | 65 | 30 |
|                                    | 650  | 400 | 250 | 125 | 60  | 30 | 15 |
| Design Speed (km/h)                | 120  | 100 | 80  | 60  | 40  | 30 | 20 |

Three-dimensional smooth road surface in TruckSim is used as the road model to set the road adhesion coefficient as 0.85 (dry road surface). According to the regulations of national standard, three working conditions (see Figure 2): ① driving speed: 120km/h, limit radius: 650m; ② driving speed: 80km/h; limit radius: 250m; ③ driving speed: 40km/h, limit radius: 60m are selected respectively to carry out simulation analysis on the lateral stability of the vehicle to observe the driving safety of the vehicle at the circle curve with the radius smaller than that regulated by the national standard at the regulated speed so as to evaluate the driving safety of the bend road section.
5. Evaluation of Driving Safety on Curves

During the simulation, the test is carried out by using the fixed speed and road circle curve radius to simulate driving of the vehicle at bend road section in actual road. The simulation result under three experimental working conditions is analyzed as below:

1) When the driving speed at bend road is 120km/h, the limit radius of road circle curve is 650m.

When the driving speed is 120km/h, the bend road sections with circle curve radius as 500m, 600m and 650m are selected respectively to analyze lateral acceleration of the vehicle when driving at above three kinds of bend roads, dynamic response of improved lateral load transfer rate $LTR_{New}$ (see Figure 3).

![Figure 3](image)

**Figure 3** Safe Driving Evaluation Simulation Results in Condition 1

It could be known from the Figure 3 that when the vehicle drives at the road section with larger circle curve radius, the lateral stability indexes of the vehicle are substantially increased at sudden change of steering wheel angle. After reaching the maximum value, the slow declining trend is stable. It indicates that the vehicle is at stable state. In the Figure 3, when the circle curve radius is 650m, the overshoot of side slip/turn stability indexes of the vehicle is small. It indicates that the vehicle just experiences the “vibration” at small amplitude. Then, it is maintained at stable state. However, when the circle curve radius declines to 600m, the kinetic response of the vehicle is large. When the lateral acceleration of the vehicle approaches 0.25g, $LTR_{New}$ will exceed 0.4. when the circle curve radius decline continuously, arriving at 500m, and when the vehicle drives at the speed of 120km/h at the bend road section, the lateral acceleration will exceed 0.4 and $LTR_{New}$ will reach 0.7. Then, it could be found that there is certain hidden safety danger and the vehicle cannot smoothly drive through the bend road section.
(2) Driving speed at the bend road is 80km/h and limit radius of circle curve is 250m
When the driving speed is 80km/h, the bend road sections with circle curve radius as 150m, 200m and 250m are selected respectively to analyze lateral acceleration of the vehicle when driving at above three kinds of bend roads, dynamic response of $LTR_{\text{New}}$ (see Figure 4).

![Fig. 4 Safe Driving Evaluation Simulation Results in Condition 2](image)

It could be known from the Figure 4 that when the vehicle drives at the road section with circle curve radius of 250m, the lateral acceleration of the vehicle is smaller than 0.4g. Meanwhile, after experiencing a small change, $LTR_{\text{New}}$ is stabilized close to 0.4. It indicates that the vehicle can drive through the bend road at stable state. However, when the circle curve radius declines to 200m, the lateral acceleration of the vehicle is increased to 0.38, approaching the related regulations of national standard. However, when it exceeds 0.6, there is large hidden driving safety danger in the vehicle when driving at the bend road section. However, the circle curve radius is further reduced to 150m, the lateral acceleration of the vehicle reaches the maximum value, and it will exceed 0.4g. However, when $LTR_{\text{New}}$ also exceeds 0.8, the vehicle is at extremely unstable state.

(3) The driving speed of the vehicle at bend road is 40km/h, limit radius of circle curve is 60m.
When the driving speed is 40km/h, the bend road sections with circle curve radius as 40m, 50m and 60m are selected respectively to analyze lateral acceleration of the vehicle when driving at above three kinds of bend roads and dynamic response of $LTR_{\text{New}}$ (see Figure 5).

![Fig. 5 Safe Driving Evaluation Simulation Results in Condition 3](image)
It could be known from the Figure 5, when the vehicle at the speed of 40km/h drives at the circle curve with the radius smaller than 60m, though the kinetic response amplitude of the vehicle is increased, the vehicle still can smoothly drive through the bend road section at stable state without the phenomenon of side slip/turn, which is a little different from the change situation of the kinetic response of the vehicle driving at the speed of 80km/h and 120km/h, for which the main reason is the low speed at that time.

6. Conclusion
According to the problem about driving safety evaluation at the bend road section, the quantitative analysis on relationship between the road circle curve radius and traffic safety at bend road section is carried out from the perspective of the lateral stability of the vehicle based on the design regulations of the national standard. According to the simulation result, it manifests that There are remarkable influences of road circle curve radius and driving speed of the vehicle at the bend road section on lateral stability. Under the working conditions of ①②, the lateral stability index of the vehicle is higher than the safety standard when the vehicle drives at the bend road section with circle curve limit radius (500m and 150m). However, under the working condition of ③, the vehicle can still drive through the bend road section when the vehicle drives at the bend road section with circle curve limit radius (50m and 40m). However, to ensure most vehicles (like heavy-duty vehicle) could smoothly drive through the bend road section, the circle curve radius of the road cannot be smaller than the limit value regulated by the national standard.

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