Research on Minimum Safe Following Distance Model of Trucks on Slope-curve Section of Expressway

Fei Zhang*, Yan Zhang
School of Highway, Chang’an University, Xi’an, Shaanxi, 710064, P. R. China
*Corresponding author’s e-mail: 591941335@qq.com

Abstract. In view of defects in the existing minimum safety distance model, a model for calculating the safe distance on slope-curve section was built based on truck brake system and by fully considering the characteristics of drivers’ driving behaviors and defining the scope of slope-curve section of expressway, and the slope acceleration parameters of “slope-environment” were proposed to effectively calibrate the model, thus providing a basis for selecting the distance value of trucks and the location of traffic signs on slope-curve section. Besides, a following model for trucks was established with TruckSim 2016 software to analyze various indicators such as vehicle slip ratios and vehicle interval value under upslope and downslope states, which verified the effectiveness of the safe distance model.

1. Introduction
In the freight transport system of China, the traffic volume of highway freight has exceeded 39 billion tons by the end of 2018, and the proportion of highway freight transportation is more than 70%, which has obvious advantages compared with other modes of freight transportation. Considering the steep terrain in some remote areas of China, the restriction of project cost and the level of regional economic development, there are many sections with small plane radius curve and large longitudinal slope in expressway design and operation. According to investigation and statistics, trucks account for about 35% of the total road vehicles types, and the number of truck accidents accounts for about 54% of the total number of highway traffic accidents [1]. Because of the large total weight of the truck itself, it is more difficult to brake under the condition of loading. If the slope-curve section can not ensure the safe driving distance, it is easy to induce traffic accidents.

At present, there are many studies on vehicles, vehicle distance and road alignment at home and abroad, but there is no in-depth research in the field of driving safety of truck in slope-curve section.Varunjikar T [2] took the special road section as the research starting point, established the calculation model, and obtained the combination form of slope-curve section in accordance with the design specification.Sarhan M et al.[3] applied the theory of safety and reliability to flat curve design and stop line-of-sight analysis.Mu [4] studied the running state of different vehicles on the slope-curve section, and provided the basis for the selection of the index value in the design of the slope-curve section according to the dynamic characteristics of the vehicle. Hu [5] according to the driver's driving workload theory, the relationship model between the workload state and the linear index of the slope-curve section is established. Among the many research objects mentioned above, the safe distance between trucks on the slope-curve section is not considered, and there is a lack of comprehensive research on the influence of traffic environment characteristics, braking performance and driving speed on the distance between trucks.
In view of this, this paper starts from the two driving states of the slope-curve section, defines the relevant parameters, establishes the safety truck distance calculation model, and carries on the simulation verification to the model in the simulation software.

2. Definition of the scope of slope-curve section
According to the different combinations of horizontal curve radius R and longitudinal slope i, the highway can be qualitatively divided into the straight section, the longitudinal section, the horizontal curve section, the slope-curve section and so on. A slope-curve section is defined as a road section with a horizontal curve radius of not more than 1000m and a longitudinal slope of not less than 3%. This paper focuses on the research and analysis from the two aspects of horizontal curve radius and longitudinal slope, combined with the definition of relevant indexes in the fourth edition of Road Survey and Design [6] and highway route design code. The research values of horizontal curve radius are 400m, 650m, 800m and 1000m. The longitudinal slope is 3%, 4% and 5%. At the same time, it meets the specification requirements of super-elevation e and composite slope ih, and fully considers driving speed V, actual driving condition and other factors. The parameter combination range of the slope-curve section of the expressway is determined, and the slope-curve section is defined as shown in Table 1.

| i | R/m | 60 | 80 | 100 | 120 |
|---|-----|----|----|-----|-----|
|   |     | e/% | ih/%| e/% | ih/%| e/% | ih/%|
| 3 | 400 | 3   | 4  | 5   | 4.2 | 5   | 5.8 |
|   | 650 | 2   | 3  | 3.6 | 4.2 | 4   | 5.8 |
|   | 800 | 2   | 2  | 3.6 | 4.2 | 4   | 5   |
|   | 1000| 2   | 2  | 3.6 | 4.2 | 4   | 5   |
| 4 | 400 | 3   | 4  | 5   | 5.7 | 6.4 |
|   | 650 | 2   | 3  | 4.5 | 5   | 5   | 6.4 |
|   | 800 | 2   | 2  | 4.5 | 5   | 5   | 6   |
|   | 1000| 2   | 2  | 4.5 | 5   | 5   | 6   |
| 5 | 400 | 3   | 4  | 5.8 | 6.4 | 7.1 |
|   | 650 | 2   | 3  | 5.4 | 5.8 | 5.8 |
|   | 800 | 2   | 2  | 5.4 | 5.8 | 5.8 |
|   | 1000| 2   | 2  | 5.4 | 5.8 | 5.8 |

3. Establishment of minimum safe driving distance model

3.1. Calculation model of minimum safe driving distance
On the slope-curve section, the front and rear trucks are driving in the same direction, when the truck immediately takes braking measures in case of emergency, the driver behind the truck immediately presses the brake pedal when he finds that the rear lights of the front truck are on, so as to ensure that the two trucks do not collide and ensure the safety of driving. As shown in figure 1, the rear truck is defined as B and the front truck is defined as A. The total driving time of the rear truck is composed of four periods: driver reaction time tB1, truck brake coordination reaction time tB2, braking acceleration increasing time tB3, braking duration tB4. In the two time periods of tB1 and tB2, the rear truck B is defined as driving at a uniform speed, and during the braking force period of the truck, the rear truck is defined as uniform deceleration. The distance of the four time periods of the rear truck B is expressed by LB1, LB2, LB3 and LB4, and the total distance is DB. In the process of braking time of the rear truck, according to the previous definition of the calculation model, the driving time of the front truck is divided into the braking acceleration increase time tA3 and the braking duration tA4. In the tA4 time period, the front truck is also defined as uniform deceleration. The corresponding driving distance of the front truck is LA3 and LA4, the total distance is DA.
In the process of two trucks following each other, when the front truck is not braking, the workshop distance is \( S \), and when the two trucks are in the stop state, the braking safety distance is represented by \( L_t \). In order to ensure driving safety, the distance between the two load workshops should be greater than the \( L_t \). Therefore, the safety distance \( S \) calculation model between two trucks driving in the same lane can be written as given:

\[
211 2 12 3 3 22 2 4 \\
S = D_B - D_A + L_t
\]

where \( V_B \) is the initial driving speed of the rear truck B, m/s; \( a_{ZB} \) is the initial slope-curve acceleration of the rear truck B, m/s\(^2\); \( V_A \) is the initial driving speed of the front truck A, m/s; \( a_{ZA} \) is the initial slope-curve acceleration of the front truck A. To facilitate discussion of safe driving distance, make assumptions as following:

Hypothetical 1: The front and rear trucks drive in the same lane, when the front truck are braking, the rear truck adopts the original lane deceleration and does not take the measures of changing lanes to avoid collision.

Hypothetical 2: Because of the same vehicle parameters, when the front truck A and the rear truck B decelerate to the stop state with the maximum braking acceleration \( a_i \), the acceleration increase time is the same: \( t_{A3} = t_{B3} = t_3 \).

Hypothetical 3: The vehicle braking acceleration increase time \( t_i \) is defined as 0.1s, and the order of magnitude of this term in the formula \((a_{ZA} - a_{ZB})t_i^2/24\) is \(10^{-3}\), so it can be ignored.

the Eq.(1) can be written as

\[
S = \left( t_{B1} + \frac{1}{2} t_{B2} + \frac{1}{2} t_{B3} \right) V_B + \frac{1}{2} V_A t_{A3} + \left( \frac{V_B^2}{2a_{ZB}} - \frac{V_A^2}{2a_{ZA}} \right) + L_t
\]

3.2. Calibration of acceleration parameters of slope-curve in model

The resistance of the environment to the vehicle is the sum of the "environment-air" resistance and the "environment-rolling" resistance, the ratio of the vector sum of the slope direction force of the total gravity of the truck body and the environmental resistance to the mass of the truck body is called "slope-environment" acceleration \( a_z \). In the course of driving, the truck is affected by air resistance, slope resistance and environment at the same time. Its longitudinal acceleration is defined as \( a_i \), which is divided into two driving states: upslope and downslope. The function of longitudinal acceleration can be written as given:
Upslope:
\[ a_i = -g \left( \sin(\text{arctan}i) + \mu \cos(\text{arctan}i) \right) - \frac{KA\rho V_a^2}{2m} \]  
(3)

Downslope:
\[ a_i = g \left( \sin(\text{arctan}i) - \mu \cos(\text{arctan}i) \right) - \frac{KA\rho V_a^2}{2m} \]  
(4)

Determine the acceleration of the slope-curve section as longitudinal acceleration \(a_i\) and braking acceleration \(a_t\), vector summation and further vector summation with transverse acceleration \(a_X\), the specific formula given below:
\[
\begin{align*}
  a_X &= \frac{V_a^2}{R} \cos(\text{arctan}e) - g \sin(\text{arctan}e) \\
  a_Z &= \sqrt{(a_t + a_i)^2 + a_X^2}
\end{align*}
\]  
(5)

Where \(e\) is the lateral superelevation value of the road, \(\%\); \(m\) is the total weight of the truck, including the net weight and load, take 65t; \(\mu\) is the adhesion coefficient, take 0.015; \(K\) is the air resistance coefficient, which is usually kept as a constant at high speed, take 0.81; \(A\) is taken as the positive windward area of the truck, take 6.82 \(m^2\); \(\rho\) is taken as the air density, \(N\cdot\text{s}^2/\text{m}^4\), take 1.22.

4. Simulation analysis
In the simulation settings, the weather condition is good. The load truck model 3A Cab Over in TruckSim 2016 database is selected, and the road horizontal curve radius and longitudinal slope are set. By inputting different road pile numbers and the elevation variation values within the width range of the road cross section at different road pile numbers, we can get the superelevation \(e\) and the composite slope \(i_h\) defined in Table 1. The simulation analysis can be divided into two driving modes: upslope and downslope.

4.1. Simulation analysis of truck following in upslope driving
An example of slope-curve section is selected for simulation as following:
\[ i = 4\%, R = 650, V_a = 70\text{km/h}, V_B = 80\text{km/h} \]

At the beginning of the simulation, the initial workshop distance is 74.0 m, and after 4 seconds of driving, the workshop distance is 62.9 m, which is the \(S\) value calculated by the Eq. (2) calculation model which needs to be verified. At this time, the front truck takes braking measures, the rear truck sees the front truck tail light on to slow down with the maximum braking acceleration, and the last two trucks stop. In the simulation process of this verification condition, the slip ratios of the front truck and the distance between the two trucks as shown in figure 2 and 3.

The acceleration of the front truck is controlled by Target Speed measures to meet the premise that the braking acceleration of the two trucks is the same. Observation and analysis of the upslope simulation output results, in the braking process of the front truck, the trend of the reduction of the distance between the two trucks is becoming more and more obvious. When both trucks decelerate and brake stop, the distance between the workshop gradually tends to 6.8m, which no longer changes, and the stopping distance meets the 3m upslope braking safety distance calibrated above. The slip ratios \(\varepsilon\) of the truck is in the range of \([0,0.2]\), the longitudinal and transverse adhesion coefficients \(\mu_Z\) and \(\mu_C\) of pavement can provide better braking performance and handling stability.
4.2. Simulation analysis of truck following in downhill driving

An example of slope-curve section is selected for simulation as following:

\[ i = 3\%, R = 1000, V_a = 100\text{km/h}, V_B = 110\text{km/h} \]

At the beginning of the simulation, the distance between the two trucks is set at 109.6m. When the distance between the two trucks is 98.5m after driving at a uniform speed for 4s, the speed of the rear truck is higher than that of the front truck, and the rear truck begins to take braking measures. It is simulated whether the speed of the rear truck is higher than that of the front truck under the condition of the same speed as the front truck to meet the requirement of non-collision. The variation of the distance between the two trucks during the simulation of this verification condition is shown in figure 4.

After the simulation of the above working conditions, the stopping distance between the two trucks is 9.8m, which meets the 5m downslope braking safety distance calibrated in the previous paper, which verifies the effectiveness of the Eq. (2) safety driving distance model.
5. Conclusion
On the premise of analyzing the definition of slope-curve section, the slope-curve combination of expressway is effectively defined. Based on the different combinations of driver reaction time, horizontal curve radius and longitudinal slope value, the minimum safe truck distance model on slope-curve section of expressway under three braking conditions is established, which takes into account the characteristic factors of "bending + slope" and the influence of environment. It can reflect the driving state of the truck more accurately, and provide the basis for the selection of the distance value and the position of the traffic sign. TruckSim 2016 software is used to simulate the two driving states of upslope and downslope under the condition of different types of slope-curve and different driving speed. The results show that the minimum safety distance obtained by the model under the conditions of different horizontal curve radius, different longitudinal slope and different speed all meet the requirements of safe driving.

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