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Numerical study of the stopping distance for runaway vehicle on truck escape ramp by using the improved equation of car driving

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Abstract. The stopping distance of the runaway vehicle on the mountain road directly affects the length design of the arrester bed. Since the subsidence depth of runaway vehicle wheel on the arrester bed is neglected in the past researches, the stopping distance estimated by the vehicle driving equation is not accurate. The purpose of this paper is to supplement the influence of subsidence depth on rolling resistance and the influence of mountain highway altitude on air resistance, and improve the estimation accuracy through improved vehicle driving equation. Firstly, the formula for fitting the subsidence depth is established, and the formula for calculating the pushing resistance and compaction resistance is added. Considering the influence of the altitude of the mountain road on the air resistance, the formula for calculating the corrected air resistance and the air lift is added too and the improved vehicle driving equation is generated. Secondly, a simulink model is established based on the improved vehicle driving equation and determine the arrester bed entering position and the initial entering speed of the runaway vehicle. Finally, the simulation model is run and analysed. The results show that the error rate of the simulation results is less than 8.0% compared with the full-scale test data. Compared with original equation, the shortening rate of the stopping distance is up to 85.59%.

Keywords. Truck escape ramp; Stopping distance; Simulink

1. Introduction

The stopping distance of the runaway vehicle on the arrester bed after entering the truck escape ramp determines the design length of the arrester bed. There are two methods about the design length: the first is direct method which calculates the length of arrester bed directly and the second is indirect method that the length of arrester bed is determined by estimating stopping distance. The direct method is the most classic of the FHWA method proposed by the US Federal Highway Administration [1]. The method assumes that the runaway vehicle that is rushed into the arrester bed performs a uniform deceleration motion, and the wheel that moves forward is only subjected to the rolling resistance and the rolling resistance coefficient is constant, regardless of the influence of the air resistance, and does not consider the influence of the wheel sinking into the arrester bed. So the estimated arrester bed length will be too short, and it may be biased to be unsafe if used in engineering[2]. Due to the simple calculation, the FHWA method is still widely used in the length



design of domestic arrester bed. More scholars have done a lot of research on indirect methods. Based on energy conservation and taking into account air resistance and other factors, STANLEY H T proposed a parking distance calculation method [3], which assumes that the rolling resistance coefficient is constant, and the difference between the actual value and the calculated result is relatively large. Domestic scholar Zhiying Yuan (2006) analysed the driving mechanics characteristics of runaway vehicles on the truck escape ramp and derived the driving equation [4]. However, this equation does not consider the influence of wheel subsidence depth on the stopping distance. Since only the rolling resistance and the slope resistance are considered, the air resistance is neglected, and the rolling resistance coefficient is constant, the estimated stopping distance is short, and the engineering application is unsafe. Yongsheng Qian(2007) based on the vehicle's downhill running resistance, comprehensively considering the air resistance, rolling resistance, slope resistance, inertial resistance and the vehicle's own motion resistance during the operation of the vehicle, calculated the set length of the downhill arrester bed[5]. But the research did not consider the compaction resistance and pushing resistance of the interaction between wheel subsidence and the gravel.

2. Improvement of car driving equation

2.1. The subsidence depth of wheels on the arrester bed

When calculating the pushing resistance, the subsidence depth value is required, and the sum of the subsidence depth and the compaction depth is equal to the total subsidence depth [6-7]. Therefore, in order to improve the calculation accuracy of the pushing resistance, in order to obtain a more accurate calculation of the stopping distance, a model of subsidence depth calculation is proposed. The method is to fit the full-scale test data from references [8] by MATLAB, and obtain the fitting formula of the subsidence depth. The formula for subsidence depth is expressed in equation (1):

$$Z = f(G, v) = 13.11 + 3.582 \times \sin(0.6571 \times \pi \times G \times v) + 0.7563 \times e^{-(0.5635 \times v)^2} \quad (1)$$

2.2. Compaction resistance

After the runaway vehicle enters the brake bed, the interaction between the wheel and the gravel is complicated. From the classic Bekker model, the compaction of the gravel by the tire will produce compaction resistance [9-10], and the concrete calculation formula is shown in equation(2):

$$R_c = P \times w \times k / n + 1 \times \left(\frac{3 \times G \times \cos(\arctan i)}{2 \times w \times k \times \sqrt{D(3-n)}} \right)^{(2n+2)/(2n+1)} \quad (2)$$

2.3. Pushing resistance

Similar to the compaction resistance, it is known from the classic Bekker model that the tire will have a pushing resistance against the gravel and the concrete calculation formula is expressed in equation(3) [9-10]. The modulus and index of deformation in the formula can be measured by static tri-axial test according to references [9-10] and the results are shown here. When the gravel relative density is 13%, 45% and 80%, the deformation modulus is 77.91, 104.44 and 175.24 and the deformation index is 1.63, 1.67 and 1.75 respectively.

$$R_b = P \cdot \frac{w}{2} \cdot Z_B^2 \cdot \gamma \left(\frac{2N}{\tan \alpha} + 1 \right) \cdot \cos^2 \left(\tan^{-1} \left(\frac{2}{3} \tan \alpha \right) \right) \cdot 0.45 \cdot g \quad (3)$$

2.4. Air lift

The formula for calculating air lift based on automobile theory[10], and then substituting longitudinal air resistance coefficient, that more accurate and more suitable air lift formula of runaway vehicles in specific mountainous areas could be obtained, such as the following formula.

$$F_z = C_{fz} \cdot b \cdot A \cdot v^2 / 21.15 \quad (4)$$

The windward area of the vehicle can be calculated by calculating formula, but the series of vehicles are too many to measure and calculate completely, so we can use its empirical values, as shown in references [2]. In the same way, the air resistance coefficient can also be determined by its empirical values, as shown in references [2].

2.5. Improvement of car driving equation

To add the compaction resistance, the pushing resistance and air lift to the vehicle driving equation, the improved vehicle driving equation is as follows:

$$F_f + F_a + F_i + F_j + R_c + R_b = 0 \quad (5)$$

By inserting the above formula (2) to formula (4) into formula (5), the improved vehicle driving equation can be obtained as is shown in equation (6):

$$\begin{aligned} & \frac{C_{fa} \cdot b \cdot A \cdot v^2}{21.14} + (G \times \cos(\arctan i) - \frac{C_{fe} \cdot b \cdot A \cdot v^2}{21.14}) \times f + G \times \sin(\arctan i) + \frac{(1 + \delta_1 + \delta_2 \times i_k^2) \times G}{g} \times \frac{dv}{dt} \\ & + P \times \frac{w \times k}{n+1} \times \left(\frac{3 \times G \times \cos(\arctan i)}{2 \times w \times k \times \sqrt{D(3-n)}} \right)^{(2n+2)/2n+1} + P \times \frac{w}{2} \times Z_B^2 \times \gamma \left(\frac{2N}{\tan \alpha} + 1 \right) \times \cos^2 \left[\tan^{-1} \left(\frac{2}{3} \tan \alpha \right) \right] \times 0.45 \times g = 0 \end{aligned} \quad (6)$$

3. Simulation

3.1. Simulink model of the stopping distance

The acceleration function can be obtained by the formula (6), and then the integral function can be used to obtain the speed function, and then the function is subjected to the definite integral from the initial speed to zero, and get the stopping distance. The acceleration function is shown in equation (7):

$$\begin{aligned} a = \frac{dv}{dt} = & \frac{C_{fa} \cdot b \cdot A \cdot v^2}{21.15} + (G \times \cos(\arctan i) - \frac{C_{fe} \cdot b \cdot A \cdot v^2}{21.15}) \times f + G \times \sin(\arctan i) + P \times \frac{w \times k}{n+1} \times \left(\frac{3 \times G \times \cos(\arctan i)}{2 \times w \times k \times \sqrt{D(3-n)}} \right)^{(2n+2)/2n+1} \\ & + P \times \frac{w}{2} \times Z_B^2 \times \gamma \left(\frac{2N}{\tan \alpha} + 1 \right) \times \cos^2 \left(\tan^{-1} \left(\frac{2}{3} \tan \alpha \right) \right) \times 0.45g \times \frac{g}{(1 + \delta_1 + \delta_2 \times i_k^2) \times G} \end{aligned} \quad (7)$$

The stopping distance is shown in equation (8). In order to calculate the stopping distance, a calculation model is established by Matlab/Simulink.

$$s = \int_{v_x}^0 \left(\int adt \right) dt \quad (8)$$

3.2. Entrance position of the arrester bed

The formula for calculating thermal failure of runaway vehicle brakes is expressed in equation (9) [5]:

$$T = -400.7 + 110.8 \ln(10^3 L) + 132.8 \ln \beta + 42.3 \ln(v_i / 3.6) \quad (9)$$

According to the GSRS system developed by the US Federal Highway Administration, for different vehicle types and different slopes, the failure temperature is limited to 260 °C, and the formula (9) is inversely solved by using L as the dependent variable and get the distance from the entrance position to the top of the slope:

$$L = 10^{-3} \times e^{\frac{[T + 400.7 - 132.8 \ln i - 42.3 \ln(v_i / 3.6)]}{110.8}} \quad (10)$$

According to incomplete statistics, the position of the runaway vehicle at the top of the slope is the position of the vehicle that is out of control when the brake is in thermal failure, that is to say, the position where the vehicle is out of control and becomes a runaway vehicle and needs to enter the truck escape ramp to perform forced deceleration stopping.

3.3. Initial vehicle velocity

In general, under the same mechanical environment, different initial velocity will get different stopping distance, and with the increase of initial speed, stopping distance will also increase. In this paper, the vehicle velocity prediction model will be used to calculate the speed. The formula of the model is as follows[13]:

$$v_x = 8.82 \times \left(0.01291 \times v_i^2 - 3.28 \times h_x - 3.28 \times f_1 \times L - 0.000033 \times v_m \times L - \frac{0.0499 \times A \times v_n^2 \times g}{G} \right)^{1/2} \quad (11)$$

So far, the thermal failure model of the brake can be used to calculate the L and then replace it into the formula (11). Obviously, the slope can be determined from the exact long slope and the initial vehicle velocity also can be obtained by solving the equation.

3.4. Analysis

The initial conditions of the data from the references [8] were substituted into the simulation model of the stopping distance to calculate the stopping distance, and compared with the results of the original equation from reference [11]. The comparison is shown in table 1. It can be seen from table 1 that under the conditions of the total mass of the two vehicles and the four different initial speeds, the calculated stopping distance of the improved vehicle driving equation is less than 8% compared with the full-scale test data; compared with the original equation, the stopping distance is greatly reduced, and the maximum reduction rate is up to 85.89%. In addition, it is found that the stopping distance calculated by the improved equation is slightly larger than the actual stopping distance, and it is biased safe for practical engineering applications. The stopping distance calculated by the original equation is also much larger than the actual stopping distance. In theory, it is biased safely in practical engineering applications, but it also wastes valuable highway resources. If limited by the topography, there will not be enough space to build a long truck escape ramp.

Table 1. Comparison of the stopping distance (m)

vehicle quality / kg	Initial velocity / $km \cdot h^{-1}$	Full-scale test data	Improved equation	Error rate(%)	Original equation	Contribution of the improved equation	
						Shortening distance	Shortening rate(%)
24642.46	66.94	36.27	38.52	6.2%	273.08	234.56	85.89%
	73.38	45.42	48.28	6.29%	327.51	279.23	85.26%
10776.37	63.72	39.93	40.82	2.22%	245.03	204.21	83.34%
	75.31	52.73	56.94	7.99%	339.70	282.76	83.24%

4. Conclusion

Using the improved vehicle equation to calculate the stopping distance, the improved equation is shown to be effective by comparing with the results of the full-scale test data and the original car equation. The contribution of the compaction resistance, the pushing resistance and the air lift added into driving equation is not only reflected in shortening the stopping distance but also has high estimation accuracy.

5. Appendix

F_f : Rolling resistance; R_b : Pushing resistance
 W : The normal pressure between wheel and
 contact surface; f : Rolling resistance
 coefficient; G : The total weight of a runaway
 vehicle; i : The slope of truck escape ramp
 F_z : Air lift force; F_t : Slope resistance
 R_c : Compaction resistance;

P : Number of wheels pushing soil on one side
 w : Section width of for vehicle wheel
 k : Deformation modulus of aggregate
 D : Wheel diameter
 α : Internal friction angle of gravel (the internal
 friction angle of the gravel aggregate from
 0.8cm to 3.2cm is 35.4°)
 T : Temperature of brake during thermal failure

γ : Weight of gravel per unit volume (and the accumulation density of gravel is $2600\text{kg} \cdot \text{m}^{-3}$)
 Z_B : Wheel depth pushed by the compaction of gravel (Theoretically, the subsidence depth is equal to compaction depth and subsidence depth is approximately equal to wheel depth when compaction depth is shallow)
 N : Local carrying coefficient (and its desirable value is 1); g : Local gravity; Z : Subsidence depth
 v : The initial vehicle velocity
 F_j : Acceleration resistance
 i_k : Transmission ratio; b : Elevation correction coefficient
 H : Average elevation; F_a : Air resistance
 A : Cross-section windward area of a vehicle
 F_z : Air lift force; C_{fz} : Vertical air drag coefficient
 β : Slope angle; i_1 : Highway slope

6. References

v_1 : The speed of a runaway vehicle running at the top of a long slope
 L : The driving distance of runaway vehicle during thermal failure of the brake
 h_x : Altitude difference (and here is the formulation: $h_x = L \times \sin(\arctan(i_1))$)
 f_1 : The rolling resistance of mountainous highway
 v_m : The average value of v_i and V_x
 v_n : The average value of v_i^2 and V_x^2
 δ_1 : The influence coefficient of inertia force on the wheels (and its range is 0.03~0.05)
 δ_2 : The inertial influence coefficient of a runaway vehicle's engine (and its range is 0.05~0.07)
 C_{fa} : Longitudinal air drag coefficient
 a : Acceleration; s : Stopping distance
 v_x : The initial velocity of the runaway vehicle when it enters the truck escape ramp

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