Journal of Architectural Research and Development, 2023, Volume 7, Issue 6
http://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Reliability Design for Longitudinal Slope Length of Expressway

Yong Yang*, Haonan Ding

China Merchants Chongqing Communications Technology Research & Design Institute Co., LTD., Chongqing 400067, China

***Corresponding author:** Yong Yang, lyhom62@sina.com

Abstract: The significance and the strategies of applying the reliability design method of longitudinal slope length in expressway engineering were explored in this study. The objective is to offer insights that can be beneficial for designing longitudinal slope lengths in contemporary expressway projects, with a focus on enhancing their reliability and safety.

Keywords: Expressway; Longitudinal slope design; Longitudinal slope length; Reliability

Online publication: November 28, 2023

1. Introduction

With the continuous development of the modern highway transport industry, the safety and reliability of longitudinal slopes have begun to attract much attention. To address the challenge of vehicles struggling on highway inclines and to prevent unnecessary traffic safety incidents, reasonable strategies should be implemented to ensure the reliability of the slope length.

2. The significance of highway longitudinal slope length reliability design

From a highway engineering point of view, the significance of the longitudinal slope length reliability design includes the following aspects: (1) Reducing the slope resistance that heavy vehicles need to overcome when going downhill, so as to reduce the downhill speed and ensure the safety of heavy vehicles. (2) Solving the difficulties of large vehicles in ascending slopes and avoiding the safety accidents caused by large vehicles skidding on the uphill slope. (3) Reducing the speed difference between different types of vehicles when going, so that the capacity and safety of highways can be significantly improved [1]. It is clear that in modern highway engineering, the reliability of the length of the longitudinal slope has a significant impact on the traveling experience and road safety. Therefore, this issue should be prioritized by designers, and effective strategies should be taken to improve the reliability of the design of the length of the longitudinal slope of the motorway.

3. The strategies of reliability design for longitudinal slope length of expressways

3.1. Selection of representative models

When designing the length of longitudinal slopes in highways, in order to ensure its reliability, the designer first needs to reasonably select a representative model (i.e., the vehicle that is most likely to have a major safety accident) [2]. In China, large vehicles and minibusses are the most common types of vehicles involved in accidents, and the number of accidents for these two vehicle types is quite similar. However, in terms of the number of casualties, the number of casualties in traffic accidents involving large vehicles is higher. Most vehicles involved in such accidents have violations such as speeding or overload [3]. FAW is the most popular brand of heavy-duty vehicles in China [4]. Therefore, designers can choose FAW load vehicles as representative models of modern highway longitudinal slope length reliability design. **Table 1** shows the parameters of an FAW tractor-trailer representative model.

Table 1. Representative model parameters of a FAW tractor

No.	Program	Gear				
		Gear VII	Gear IX	Gear X	Gear XI	Gear XII
1	Shift speed, V_b	41.68 km/h	53.53 km/h	68.15 km/h	88.12 km/h	112.54 km/h
2	Dynamic parameter, W	2.23E-02	1.73E-02	1.36E-02	1.05E-02	8.25E-03
3	Dynamic parameter, Q	1.93E-03	1.17E-03	7.23E-04	4.32E-04	2.65E-04
4	Dynamic parameter, P	-3.03E-05	-1.47E-05	-7.49E-06	-3.86E-06	-2.23E-06
5	Inertia coefficient δ	1.209	1.138	1.097	1.070	1.055

3.2. Calculation of longitudinal slope length

After determining the representative model, the vehicle will be used as the basis for determining the length of the longitudinal slope in the expressway. When the vehicle is traveling on the slope section, its transmission will usually change between different gears, and in the process of changing gears, the engine will also provide different traction for the vehicle, which results in the acceleration and deceleration of the vehicle [5]. The vehicle decelerates until it reaches a uniform speed, and equation (1) can be used to calculate the slope length:

$$\lambda L = \frac{\delta}{12.96g}\int_{v_1}^{v_2} \frac{v}{Pv^2 + Qv + [W - \frac{(f+i)}{\lambda}]} dv \tag{1}$$

where λ represents the correction coefficient, where the value is 1, L represents the length of the longitudinal slope, g represents the acceleration of gravity, where the value is 9.8 m/s^2, v_1 represents the vehicle travelling speed before shifting gears, v_2 represents the vehicle traveling speed after shifting gears, v represents the vehicle's running speed on the horizontal road surface, f represents the drag coefficient of the rolling tires, where the value is 0.01, i represents the longitudinal slope, d represents the width of the longitudinal slope.

3.3. Scientific analysis of reliability function

Reliability refers to the probability of the structure performing its function within a specific period and conditions [6]. The structure is said to be reliable if it can perform its expected functions; otherwise, it would be deemed unreliable. The critical point between the reliable and unreliable state is called the limit state. By creating a functional expression linked to an engineering structure reaching this limit state, allows for a systematic evaluation of the structure's reliability [7]. With this approach, expressway designers can incorporate the aforementioned reliability theory into their designs. They can utilize the failure rate to depict the design value of the longitudinal slope that falls outside the safety range and indicates potential safety risks [8]. During this process, if the length and design of the slope allow the vehicle to ascend without slowing down to the minimum allowable speed, the designer can conclude that the vehicle can safely navigate the longitudinal slope section. The slope length required to ensure the safety of the vehicle while navigating the slope is called the safety value, and the slope length that is determined during the design process is called the design value. In the reliability design of longitudinal slope length, if the design value of slope length is smaller than the safety value, it indicates that the longitudinal slope length design of the expressway project is reliable [9]. If the design value is greater than the safety value, it indicates that the longitudinal slope length design of the expressway project is not reliable, and the longitudinal slope length design poses safety risks. Based on this theory, the reliability function of its longitudinal slope length can be expressed through equation (2):

$$Z = L - S \quad (2)$$

where Z represents the reliability function of the expressway longitudinal slope length, L represents the safe value, which can be calculated using formula (1); and S represents the design value. Equations (1) and (2) involve many functional variables. So for the convenience of research, the designer can use the vehicle speed and slope at the entrance of the ramp as random variables, and use other parameters as deterministic variables. In the subsequent study, the slope change can be standardized, while the movement speed needs to be obtained by using field measurements. In order to obtain the vehicle movement speed parameters of China's highway longitudinal slope entrances under different speed design conditions, the designer can use the MetroCount 5600, a specialized vehicle typing statistical system, to classify the models and measure the vehicle speeds. According to the current design speed of China's highways, in this study, three types of longitudinal slope inlet design speed of highways were selected for investigation, which were 80 km/h, 100 km/h, and 120 km/h, respectively. After obtaining the corresponding vehicle travel parameters, SPSS software was used to carry out the K-S one-sample test of the data. **Table 2** shows the K-S one-sample test data of the survey results of vehicle traveling speed at the entrance of the longitudinal slope of the motorway.

Table 2. K-S single sample test data of the vehicle speed survey results at the longitudinal entrance of the expressway

No.	Program	Design speed		
		80km/h	100km/h	120km/h
1	Sample size	239	248	313
2	Mean value of normal parameters	74.779	78.597	80.894
3	Normal parameter standard deviation	6.575	7.147	7.072
4	Maximum positive difference	0.04622	0.00369	0.02455
5	Maximum negative difference	-0.4143	-0.02563	-0.3412
6	Absolute value of the maximum difference	0.04622	0.00369	0.03412
7	Test statistics	0.04622	0.03369	0.03412
8	Progressive significance	0.2	0.2	0.2
9	Exact significance	0.669	0.932	0.847

Through the above data analysis, it was found that under the three design speed conditions, the accurate significance of the statistical value of the vehicle traveling speed at the longitudinal slope entrance exceeded the significant level value (0.05), so its distribution was considered to be normal.

3.4. Verification of the reliability of the longitudinal slope length

According to China's Highway Route Design Code JTG D20-2017, for expressways with design speed of 80 km/h, 100 km/h, and 120km/h, the maximum slope design index should be controlled at 5%, 4%, and 3% respectively, and under certain circumstances, the slope can be reduced by 1%. In practice, since the strict criteria for the maximum longitudinal slope do not often directly impact the design, there is usually no need to further examine the probability of it failing in specific designs [10]. Under these three conditions, the minimum value of the longitudinal slope length of the motorway was 200 m, 250 m, and 300 m respectively; the maximum permissible speed when ascending the slope was 50km/h, 55km/h, and 60km/h, respectively. Using MATLAB software, designers can perform sampling simulation calculations to verify the reliability of the design value for downhill slope length across different design speeds, slopes, and slope lengths.

After calculation, it was found that when the design speed was 80km/h, the maximum slope length was 700 m, with a slope length reliability is 74.874%; when the design speed was 100km/h, the maximum slope length was 800 m, with a reliability of 86.555%; when the design speed was 120km/h, the maximum slope length was 900 m, with a reliability of 95.581%. However, according to the Unified Standard for Reliability Design of Highway Engineering Structures (JTG 2120-2020), when the design speed of the longitudinal slope opening is 80 km/h, 100 km/h, and 120km/h, the corresponding target reliability should reach 85%, 90%, and 95%, respectively. Therefore, it is clear that when the design speed of the longitudinal slope was 80 km/h and 100 km/h, the maximum length of the longitudinal slope calculated did not meet the actual safety requirements of the vehicle.

3.5. Determination of the safety value of longitudinal slopes

The calculation of the maximum value for the longitudinal slope length is based on typical conditions for maximum slope values. However, to determine the safety length of the longitudinal slope under specific circumstances, designers can consider reducing the maximum slope value by 1%. They can then gradually increase the maximum slope value and perform sampling simulation calculations to obtain the safety value for the slope length [11]. **Table 3** shows the results of the sampling simulation calculation of slope length safety value under the condition of different maximum slope values.

Table 3. Sampling simulation results of slope length safety values under different maximum slope values

No.	Design speed	Maximum gradient	Maximum slope length
1	80km/h	4%	850 m
2	80km/h	4.2%	800 m
3	80km/h	4.4%	700 m
4	80km/h	4.6%	600 m
5	80km/h	4.8%	550 m
6	80km/h	5%	500 m
7	100km/h	3%	1100 m
8	100km/h	3.2%	1000 m
9	100km/h	3.4%	800 m
10	100km/h	3.6%	800 m
11	100km/h	.3.8%	700 m
12	100km/h	4%	700 m
13	120km/h	2%	Unlimited

Table 3. (Continued)

No.	Design speed	Maximum gradient	Maximum slope length
14	120km/h	2.2%	Unlimited
15	120km/h	2.4%	1700 m
16	120km/h	2.6%	1400 m
17	120km/h	2.8%	1300 m
18	120km/h	3%	900 m

Based on the data analysis, it is clear that when the maximum longitudinal slope of the expressway is reduced appropriately, the safety value of the longitudinal slope length will change accordingly, and there may even be no limit to the safe length. Based on this, the maximum gradient of the longitudinal slope can be designed according to the actual operation of the expressway, and the design value of the slope length can be determined scientifically. In this way, the length of the longitudinal slope of the highway can be designed with sufficient reliability, and the safety of vehicles navigating the slope can be ensured [12].

4. Conclusion

In summary, the longitudinal slope length design is crucial in the design of highways. In order to ensure the reliability of the longitudinal slope length design, the design strategy should be outlined clearly. Besides, suitable representative models should be selected so that the longitudinal slope length can be determined reasonably. Besides, the scientific analysis of the reliability function, the effective validation of the reliability of the longitudinal slope length, and the reasonable determination of the longitudinal slope safety length value are also crucial aspects in determining a reliable slope length. In this way, the reliability of the design value of the longitudinal slope length of the motorway can be effectively guaranteed, and traffic accidents caused by the unreasonable design of the longitudinal slope length can be avoided.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Lu L, Sun G, Li C, Gao S, 2023, Research on Speed Limit Method of Expressway on Rainy Days with Different Longitudinal Slopes. Road Traffic Management, 2023(09): 56–60.

[2] Zhang H, Tu Z, Tian S, 2022, Reliability Design of Climbing Lane Length on Mountainous Expressway. Journal of Wuhan University of Technology (Traffic Science and Engineering), 2022(03): 495–500.

[3] Chen X, 2020, Study on Key Indicators of Graphic Design of Transition Section of Highway Profile and Lane Number Change in Urbanization Area, dissertation, Huazhong University of Science and Technology.

[4] Ji P, 2018, Route Design and Technical Index Selection of Mountain Expressway. Engineering Technology Research, 2018(11): 152–153.

[5] Li M, 2019, Study on the Length of Intercrossing and Deceleration Lanes of Different Types of Expressways, dissertation, Chang'an University.

[6] Jia J, 2020, Study on Expressway Variable Speed Lane Length and Minimum Clear Distance of Interchange,

dissertation, Hebei University of Technology.
[7] Gao H, 2022, Longitudinal Slope Design of Huangxi Highway Based on Velocity Prediction Model. Transportation Science and Management, 2022(24): 63–65.
[8] He X, Xue X, Liu X, et al., 2021, Design of Winch Hoisting System for Long Inclined Shaft with Large Longitudinal Slope in Mountainous Area. Yunnan Hydropower Generation, 37(6): 38–42.
[9] Su D, 2022, Research on Design Index of Steep Slope and Gentle Slope of Expressway. East China Highway, 2022(2): 82–83.
[10] Chen X, Wu R, Deng H, et al., 2021, Analysis of Highway Longitudinal Slope and Slope length Based on Slope Climbing Ability of Dongfeng Tianlong Tractor. China and Foreign Highway, 41(5): 6–10.
[11] Behtash M, Alexander-Ramos MJ, 2022, A Reliability-Based Formulation for Simulation-Based Control Co-Design Using Generalized Polynomial Chaos Expansion. Journal of Mechanical Design, 2022(5): 144.
[12] Tran H, Thai HT, Uy B, et al., 2022, System Reliability-Based Design of Steel-Concrete Composite Frames with CFST Columns and Composite Beams. Journal of Constructional Steel Research, 194: 107298.