Research on Design Index for Continuous Uphill Gentle Slope of Expressway in Mountainous Area

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Abstract. On the basis of analyzing the measured data of the uphill slope and establishing the relationship model between the decrease of truck operation speed and the traffic accident rate, put forward admissible speed reduction standard. According to the distribution of truck load truckload tonnage and power weight power-weight ratio, select the researching dominant vehicle comprehensively. The design index of uphill gentle slope is obtained based on recovering the operation speed of trucks and considering the climbing performance curve of the leading vehicle on the uphill gentle slope section. The research results can provide a reference for the design of uphill gentle slope of expressway in mountainous area.

1. Introduction

In order to adapt to the complex terrain conditions in mountainous areas, on the premise of overcoming the height difference without excessively extending the highway length and guaranteeing driving safety of heavy-duty trucks, continuous longitudinal slopes with alternate steep slopes and gentle slopes are generally adopted in highway design. Design Specification for Highway Alignment (JTG D20-2017) stipulates that the continuous upslopes of highways should be adjusted according to the uphill speed of heavy-duty trucks. Gentle slopes should be designed in different longitudinal slopes which are not longer than the maximum slope length specified in the “Specifications”. When the design speed is ≤80km/h, the slope of the gentle slope should be ≤3%; when the design speed is >80km/h, the slope of the gentle slope should be ≤2.5%; the length of the gentle slope should not be less than the minimum slope length of the longitudinal slope[1]. The “Specification” classifies highway gentle slope indexes into two categories according to design speed, and only specifies the minimum slope length corresponding to design speed, but not raising specific requirement requirements for different slope lengths.

Therefore, it is necessary to study design indexes for gentle upslopes. In this paper, based on the selection of the allowable reduced speed and the dominant vehicle type, to restore the operating speed of heavy-duty trucks, the upper limit of the gentle slope and the gentle slope length for heavy-duty trucks to recover different operating speeds under different designed speeds are studied considering the gentle upslope climbing performance curve of the dominant vehicle type, expecting to provide a reference for designers.

2. Allowable reduced speed

By investigating the truck operating speed on continuous upslopes of Zhuji-Yongjia Highway, Ningbo-Taizhou-Wenzhou Highway and Hangzhou-Jinhua-Qzhou Highway in Zhejiang Province, and calculating the traffic accident rate of the experimental section, the relationship model between the reduced speed of heavy-duty trucks and the traffic accident rate is established, and the allowable reduced speed for heavy-duty trucks is determined.
2.1 Determination of relationship model
The reduced speed of heavy-duty trucks and the traffic accident rate in the experimental section are shown in Table 1.

| Section | Reduced speed(km/h) | Speed standard deviation(km/h) | Million-vehicle-accident rate per km times (km×10⁻⁸ Veh⁻¹)¹ |
|---------|---------------------|-------------------------------|---------------------------------------------------------|
| 1       | 20.8                | 10.058                        | 45.0                                                    |
| 2       | 17.4                | 7.432                         | 34.0                                                    |
| 3       | 10.0                | 5.913                         | 28.7                                                    |
| 4       | 15.0                | 6.961                         | 32.2                                                    |
| 5       | 12.2                | 5.741                         | 28.1                                                    |
| 6       | 13.1                | 6.331                         | 30.0                                                    |
| 7       | 9.8                 | 5.032                         | 26.0                                                    |
| 8       | 10.6                | 4.983                         | 25.9                                                    |
| 9       | 14.6                | 5.212                         | 30.7                                                    |
| 10      | 16.2                | 6.131                         | 33.5                                                    |
| 11      | 19.2                | 9.242                         | 39.2                                                    |

Based on SPSS software, the mathematical statistics method is used to carry out regression analysis on the relationship between the reduced speed of heavy-duty trucks and the traffic accident rate in continuous upslope sections. The reduced operating speed (\( \Delta v \)) is the independent variable and the traffic accident rate (\( y \)) is the dependent variable.

2.1.1 Linear regression analysis. Based on 95% confidence, the SPSS software is used for data analysis, and the results are shown in Table 2.

Table 2. Quadratic relationship model between the traffic accident rate and the reduced speed of heavy-duty trucks.

| Model | R       | R²      | R² adjustment | Standard deviation | df | F        | Sig·F |
|-------|---------|---------|---------------|--------------------|----|----------|-------|
| 1     | 0.985   | 0.969   | 0.964         | 0.995              | 14 | 189.929  | 0     |

As shown in Table 2, the multiple correlation coefficient of the quadratic relationship model between the traffic accident rate and the reduced speed of heavy-duty trucks is 0.985, and the judgment coefficient is adjusted to 0.964, both of which satisfy the requirements. The significance probability of F is 0. The relationship between each independent variable and the corresponding dependent variable is significant. Therefore, the quadratic relationship model equation obtained by statistical regression has significance.

2.1.2 Determination of relationship model. According to the determined quadratic linear regression model of the traffic accident rate and the reduced speed of heavy-duty trucks, the relationship curve shown in Figure 1 is obtained.
Figure 1. Relationship between the traffic accident rate and the reduced speed of heavy-duty trucks. The relationship model is as follows:

\[ y = 0.132\Delta v^2 - 2.484\Delta v + 38.863 \]  

(1)

2.2 Determination of the allowable reduced speed

According to the relationship model between the traffic accident rate and the reduced speed of heavy-duty trucks, when the operating speed is reduced by 10~15km/h, the traffic accident rate increases slightly with the decrease of the operating speed. When the speed is reduced by above 15km/h, the traffic accident rate increases substantially with the reduction of the operating speed. Therefore, considering traffic safety and the universality and applicability of the research results, the reduced speed of 15km/h and 20km/h is taken as the maximum allowable reduced speed of heavy-duty trucks.

3. Selection of the dominant vehicle type

The power-to-mass ratio is an important parameter for studying longitudinal slopes. It can not only determine the power obtained by the unit weight of a vehicle, but also reflect the power performance[2]. However, China adopts different power-to-mass ratios of heavy-duty trucks. To guarantee the universality and applicability of the research results, the power-to-mass ratio of 15% is selected as the research parameter to meet the running requirements of most trucks, and the dominant vehicle type on longitudinal slopes is determined[3].

According to the development status of the truck industry, the distribution of vehicle types, the load tonnage, and the national specifications on the external size, axle load and mass limit of trucks, heavy-duty trucks are determined as the dominant vehicle type. By investigating the dominant heavy-duty trucks running in Zhejiang highway network and collecting the weighing data of the weighing instrument in toll stations, the distribution of heavy-duty truck types and the total weight ratios is obtained (Figure 2). The proportion of combination vehicles is 60%, and the heavy-duty trucks with the proportion of 85% is 46.74t.

![Figure 2. Distribution of heavy-duty truck types and total weight ratios.](image-url)
According to relevant specifications\cite{5}, for combination vehicles, the maximum width is 2550mm, the maximum height is 4000mm, and the maximum allowable total mass is 49t. By comparing the sales volume of heavy-duty truck manufacturers in China, the FAW J7 tractor CA4250P77K25T1E5 is selected as the dominant model, and its power-to-mass ratio is 7.58kw/t.

4. Gentle upslope design indexes

4.1 Climbing performance curve of the dominant vehicle type on gentle slope

Considering the requirements of the Specification, the minimum allowable speed of heavy-duty trucks is the initial speed climbing the slope. Figure 6 shows the climbing performance curve of the dominant vehicle type climbing the slope on the highways with the design speeds of 120km/h, 100km/h and 80km/h. The slope of the longitudinal slope is lower than the maximum longitudinal slope with unlimited length. Figures (a), (b), represent the initial speed climbing the slope of 65 km/h, 60 km/h, respectively.

![Figure 3. Upslope climbing performance curve of the dominant vehicle type.](image)

4.2 Gentle upslope design indexes

4.2.1 Slope. According to the climbing performance curve of the dominant vehicle on the upslope section. From the perspective of effectively recovering the operating speed of the truck, the minimum recovered operating speed should be greater than 5km/h, and the slope of the longitudinal slope corresponding to the recovered operating speed of 5km/h is called the maximum gentle upslope, as shown in Table 3. The uphill section of expressway with relatively small traffic volume and strict terrain conditions takes the value in "()".

| Design speed(km/h) | 120 | 100 | 80 |
|-------------------|-----|-----|----|
| Gentle slope maximum value(%) | 1.20(1.60) | 1.60(1.90) | 2.20(2.70) |

4.2.2 Slope length. In order to provide a selection reference for the designers, and based on upslope climbing performance curve shown in Figure 6, the paper list the slope and length of gentle slopes corresponding to the operating speed recovery of 5 km/h, 10 km/h and 15 km/h at different design speeds, as shown in Table 4, Table 5, and Table 6. The uphill section of expressway with relatively small traffic volume and strict terrain conditions takes the value in "()".

| Recovered speeds(km/h) | 0.5 | 0.7 | 0.8 | 1.0 | 1.2 | 1.5 | 1.6 |
|------------------------|-----|-----|-----|-----|-----|-----|-----|
| Slope(%)               |     |     |     |     |     |     |     |
| Design speed(km/h)     | 120 | 100 | 80  |     |     |     |     |
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5. Conclusion
Based on the measured speed of trucks and the traffic accident rate, this paper establishes the relationship model between the reduced operating speed and the traffic accident rate, and obtains the allowable speed reduction value standard. Through relevant investigation and statistics, heavy-duty trucks were selected as the dominant vehicle type combined with the relevant standards. Meanwhile, the definition criteria of the gentle upslope were proposed. Based on the effective recovery of the operating speed on upslopes, the gentle upslope indexes were proposed. Finally, according to the climbing performance curve of the dominant vehicle type in gentle upslope sections, the design indexes of the gentle upslope length were put forward based on the speed recovery.

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## Table 5. Slope length corresponding to different recovered operating speeds at the design speed of 100km/h.

| Recovered speeds(km/h) | 0.5 | 0.7 | 0.8 | 1.0 | 1.2 | 1.5 | 1.6 | 1.8 | 1.9 |
|------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 5                      | 250 | 300 | 350 | 400 | 600 | 1200| 1500|     |     |
|                        | (180)| (200)| (250)| (300)| (350)| (500)| (800)| (1100)| (1500)|
| 10                     | 600 | 800 | 900 | 1200| 2000|     |     |     |     |
|                        | (400)| (500)| (550)| (650)| (1050)| (2000)| (2500)|     |     |
| 15                     | 1200| 1500| 2000| 2500|     |     |     |     |     |
|                        | (700)| (900)| (1100)| (1700)| (2500)|     |     |     |     |

## Table 6. Slope length corresponding to different recovered operating speeds at the design speed of 80km/h.

| Recovered speeds(km/h) | 0.5 | 0.7 | 0.8 | 1.0 | 1.2 | 1.5 | 1.8 | 2.0 | 2.2 | 2.5 | 2.7 |
|------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 5                      | 150 | 200 | 200 | 250 | 300 | 400 | 500 | 800 | 1500|     |     |
|                        | (60) | (70)| (90)| (120)| (150)| (200)| (250)| (400)| (700)| (1200)| (2000)|
| 10                     | 300 | 350 | 400 | 500 | 600 | 900 | 1400|     |     |     |     |
|                        | (150)| (180)| (200)| (250)| (350)| (550)| (750)| (1600)| (2000)|     |     |
| 15                     | 600 | 650 | 700 | 900 | 1200| 2000|     |     |     |     |     |
|                        | (300)| (350)| (450)| (550)| (750)| (1200)| (1800)|     |     |     |     |
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