Research on Gentle Slope Design Index of Continuous Downhill Slope Section of Mountainous Highway

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Abstract: In order to ensure the safe driving of heavy trucks, the mountainous highways have stipulated the average longitudinal slope and slope length of continuous downhill slopes. For the continuous downhill sections, the necessity of gentle slopes exists, and it is proposed to meet the average longitudinal slope conditions. The gentle slope and slope length index have certain guiding significance for the design of the longitudinal section of continuous downhill section controlled by the average longitudinal slope index. In this paper, the relationship between the running speed characteristics of the downhill truck and the slope of the vertical slope and the traffic accident rate are analyzed. The FAW Jiefang J7 tractor CA4250P77K25T1E5 with the total weight of 48.805t and the power quality ratio of 7.58kw/t is selected as the leading model, based on the downhill slope. Reduce the speed, combined with the braking performance curve of the slow-slope section of the dominant model, the research shows the design index of the downhill gentle slope.

1. Introduction
In order to overcome the height difference, continuous longitudinal slopes are often used in the design of mountainous highways within a certain distance, and the alternation of steep slope and gentle slope is often used in continuous longitudinal slope design, forming so-called "stepped" continuous long downhill section[1]. The speed of heavy truck increases rapidly. When driving in this downhill section, drivers often choose to rely on brake to decelerate. Frequent braking will cause a significant increase in the temperature of the brake hub. When the temperature exceeds 260 ℃, the brake hub thermal recession leads to braking failure, which is not conducive to the safe driving of large trucks[2~3]. Therefore, it is necessary to set a gentle slope between steep slopes of continuous downhill section, and it can effectively reduce the speed of downhill section of truck.

Based on the actual traffic situation of highway at present, this paper measured and analyzed the speed characteristics of large trucks on downhill slope of highway in mountainous area, and the relationship between longitudinal slope and traffic accident rate. According to the influence of the downhill section on the running speed of the truck, combined with the braking performance curve of the downhill section, the index of gentle slope and slope length of downhill section is studied, which provides theoretical basis for the design of gentle slope of long downhill section of mountain highway and improves its safety level.

2. Traffic characteristics of downhill section

2.1. Analysis of Running Speed Characteristics of Downhill Section
Based on the investigation of the running speed of heavy trucks in the slope bottom section of several
continuous downhill sections of highway, the average speed of large trucks in more than 50% sections is higher than 80 km/h, the maximum average speed is 92.2 km/h, and the 85% speed of large trucks in more than 50% sections is higher than 90 km/h, and the maximum 85% speed is 97 km/h. Investigate the vehicle parameter configuration given by domestic large truck manufacturers. The maximum speed of general large trucks is 90-110 km/h. The actual running speed of most large trucks is very high, which is close to the maximum speed of vehicle performance configuration.

2.2. Traffic safety analysis of downhill section

2.2.1. Traffic Accident Patterns and Causes of Downhill Section

According to the analysis of accident statistics, the main traffic accidents in the continuous downhill section of highway are rear-end collision, co-directional scraping and collision fixed objects, accounting for 44%, 19% and 16% respectively. The main causes of traffic accidents in the continuous downhill section of highway are overspeed and braking failure, accounting for 47% and 32% respectively.

2.2.2. Road alignment index at traffic accident occurrence point

The occurrence of traffic accidents is directly related to the road alignment of the road section, and it is also a powerful evaluation index of the road profile design. The relationship between different downhill gradients and traffic accidents is analyzed by statistics of the longitudinal slope gradient of the accident location in downhill section. Meanwhile, we study the relationship between the average longitudinal slope of the distance before the accident site and the accident rate.

As shown in figure 1, 2, the relationship between average longitudinal slope and traffic accident is analyzed by the average longitudinal slope of 1 km and 3 km before the traffic accident occurrence point.

![Figure 1. The Relation Diagram between the Average Longitudinal Slope and Traffic Accident 1 km before the Accident Occurrence Point](image1)

![Figure 2. The Relation Diagram between the Average Longitudinal Slope and Traffic Accident 3 km before the Accident Occurrence Point](image2)

It can be seen that there is a significant correlation between the average longitudinal slope and the probability of traffic accidents. When the average longitudinal slope is higher than 3%, the probability of traffic accidents and the accident mortality rate are significantly increased. So, it is necessary to study the index of gentle slope gradient and slope length under the condition of average longitudinal slope.

3. Selection of longitudinal slope leading vehicle type

According to the conclusion of the investigation on the power-mass ratio of trucks on highway, referring to relevant research, combined with the selection of the reference factors of the leading type, it is determined that the leading type is a six-axle truck train, the total weight should be close to 49t, the power-mass ratio should be 7.04-8.43 kw/t, and it should be close to 7.63 kw/t.

After investigating the sales of domestic truck manufacturers, the top three are FAW, Dongfeng and
Heavy Truck respectively. Comparing comprehensively, FAW Jiefang J7 tractor CA4250P77K25T1E5 is chosen as the leading vehicle type. The specific technical parameters can be found in the production instructions.

4. Calculation and analysis of design index of downhill gentle slope

4.1. Definition Basis
When a driver drives a heavy truck, there is an expected speed, as shown in table 1[4].

Table 1. Expected Speed of Large Vehicles on Expressway with Different Design Speed.

| Design speed (km/h) | 120 | 100 | 80 |
|---------------------|-----|-----|----|
| Expected speed (km/h) | 80  | 80  | 80 |

In the continuous downhill section, after the expected speed of the vehicle in the forward section is reached in a short time, the driver will keep the speed of the vehicle basically stable in an acceptable range based on driving experience and safety considerations[5]. For the back section, when the speed of the vehicle reaches the upper limit acceptable to the driver, drivers need to brake frequently, through brakes for a long time and frequently, the temperature of the brake hub rises sharply, which eventually leads to braking failure, that is very harmful to traffic safety.

When the heavy truck is running downhill, without braking, the resistance of the vehicle is greater than the force of gravity, and the vehicle will slow down. For the continuous downhill section, reducing the running speed of the heavy truck is beneficial to road traffic safety. The longitudinal slope under this condition is called the critical value of the downhill gentle slope.

4.2. Critical value of downhill gentle slope
When the gradient of the longitudinal slope of the road makes the heavy truck use engine brake or exhaust brake downhill instead of brake to maintain a uniform speed, if the actual design gradient is less than this gradient, the vehicle shows deceleration, then the gradient is called the critical value of downhill gentle slope.

The research on longitudinal slope index of downhill gentle slope section should be based on the upper limit of running speed acceptable to drivers, and combined with the measured running speed data of heavy trucks on continuous downhill section, we found that the maximum average running speed of each section is 92.2 km/h and the maximum 85% position speed is 97 km/h. The average running speed of the total survey section is 83.1 km/h and the 85% position speed is 89.2 km/h. Comparing with Table 1, it can be seen that the average speed of the heavy truck in the total survey section is 3.1 km/h higher than the driver's expected speed, and the 85% position speed is 9.2 km/h higher than the driver's expected speed. Therefore, the maximum acceptable running speed of heavy truck drivers in continuous downhill section is about 90 km/h, and the initial operating speed of the downhill gentle slope section is 90 km/h.

According to the force analysis of the vehicle in the longitudinal section, when the vehicle does not take auxiliary braking measures, the acceleration in the downhill section is \( a = 0 \), and the corresponding downhill longitudinal gradient can be obtained, as shown in formula 1.

\[
i = \frac{\lambda \cdot K \cdot A \cdot v^2}{21.25 \cdot m \cdot g} + f
\]

In the formula: \( \lambda \) - Altitude correction coefficient, Zhejiang Province takes 0.98; \( K \) - air resistance coefficient; \( A \) - Vehicle windward area, \( m^2 \); \( v \) - Relative speed between vehicle and air, km/h; \( m \) - The total weight of the vehicle, kg; \( g \) - Gravity acceleration, \( 9.81 m/s^2 \); \( f \) - Rolling resistance coefficient.

According to formula 1, the critical value of downhill gentle slope deceleration for dominant vehicle only relying on road resistance to decelerate without auxiliary braking measures, as shown in table 2.

Table 2. The critical value of downhill gentle slope deceleration for dominant vehicle only relying on road resistance without auxiliary braking measures.

| Design speed (km/h) | 120 | 100 | 80 |
|---------------------|-----|-----|----|
| Critical value of downhill gentle slope (%) | 2.00 | 2.00 | 2.00 |
In the same way, use the formula in Document [6] as a reference, the critical value of the downhill gentle slope of the main vehicle which adopts engine braking measures to decelerate can be calculated, as shown in table 3. The critical value of downhill gentle slope decelerated by exhaust braking measures can be calculated for the dominant vehicle type, as shown in table 4.

Table 3. Critical value of downhill gentle slope decelerated by engine braking measures for dominant vehicle.

| Design speed(km/h) | 120  | 100  | 80   |
|-------------------|------|------|------|
| Critical value of downhill gentle slope (%) | 3.00 | 3.00 | 3.00 |

Table 4. Critical value of downhill gentle slope decelerated by exhaust braking measures for dominant vehicle.

| Design speed(km/h) | 120  | 100  | 80   |
|-------------------|------|------|------|
| Critical value of downhill gentle slope (%) | 3.30 | 3.30 | 3.30 |

Comparing the critical values of the downhill gentle slopes in figure 10, figure 11 and figure 12, it can be seen that the critical value of gentle slope calculated by the dominant vehicle without auxiliary braking is the smallest. But no auxiliary braking means that the driver uses neutral sliding in the continuous downhill section, which violates the safety driving regulations, so it is not considered. Compared with exhaust braking, the gentle slope value required by engine braking is smaller. In order to make the research results universal, the critical value of gentle slope in downhill section of dominant vehicle type is calculated by engine braking.

4.3. Braking performance curve of leading vehicle on downhill gentle slope section

Gentle slope design is to reduce the increasing speed of vehicles in the front steep slope section, reduce the frequency of heavy truck drivers using brake, delay the increase of brake drum temperature, and reduce the probability of traffic accidents caused by brake failure of heavy trucks.

In different gears, the acceleration of the vehicle in the downhill section is calculated as follows:

$$a = \frac{g}{\delta} \left( i - \frac{\lambda \cdot K \cdot A \cdot v^2}{21.25 \cdot m \cdot g} - f - \frac{T_e \cdot \gamma}{\eta \cdot r \cdot m \cdot g} \right) \tag{2}$$

Combining formula 3, formula 4 can be obtained:

$$S = \frac{1}{12.96 \cdot f} \int_{v_1}^{v_2} \frac{v}{a} dv \tag{3}$$

In the formula: $v_1$ - Initial velocity, km/h; $v_2$ - Final velocity, km/h.

$$\lambda S = \frac{\delta}{12.96 \cdot f} \int_{v_1}^{v_2} \frac{v dv}{(i - \frac{\lambda \cdot K \cdot A \cdot v^2}{21.25 \cdot m \cdot g} - f - \frac{T_e \cdot \gamma}{\eta \cdot r \cdot m \cdot g})} \tag{4}$$

According to formula 4, the braking performance curve of the main vehicle, which relies on engine braking at the initial speed of 90 km/h, is obtained on the section with the longitudinal gradient lower than the critical value of the downhill gentle slope, as shown in figure 3.
4.4. Design Indicators of Downhill Slope

4.4.1. Downhill gentle slope gradient
From the perspective of effectively reducing the running speed of the vehicle, the lowest running speed should be greater than 5km/h. The longitudinal slope gradient corresponding to 5km/h running speed reduction of dominant vehicle should be called the maximum value of downhill gentle slope, the downhill gentle slope used in actual engineering design should not be greater than the value in table 5.

Table 5. Maximum value of gentle downhill slope of highway.

| Design speed (km/h) | 120  | 100  | 80  |
|---------------------|------|------|-----|
| Maximum gentle slope (%) | 2.80 | 2.80 | 2.80 |

4.4.2. Slope length of downhill gentle slope
Table 5 shows the maximum value of the downhill gentle slope of highway. For the same grade slope, in a certain range, different slope length have different running speed of vehicle reduction, the longer the slope length is, the greater the reduction value of running speed is. Therefore, the slope length of the longitudinal slope should be reasonably selected according to the need to reduce the running speed. Based on the braking performance curve of the dominant vehicle type shown in figure 3, this paper lists the gentle slope gradient and slope length corresponding to the speed reduction of 5 km/h, 10 km/h, 15 km/h and 20 km/h of each designed highway, as shown in table 6.

Table 6. Design Speed Highway Reduces Slope Length of Downhill Slope Corresponding to Different Running Speed.

| Velocity Decrease Value (km/h) | 0.5  | 0.8  | 1.0  | 1.2  | 1.5  | 1.8  | 2.0  | 2.2  | 2.5  | 2.8  |
|-------------------------------|------|------|------|------|------|------|------|------|------|------|
| 5                             | 150  | 180  | 200  | 250  | 300  | 350  | 400  | 500  | 800  | 1500 |
| 10                            | 300  | 350  | 400  | 450  | 500  | 650  | 800  | 1000 | 1500 | —    |
| 15                            | 400  | 500  | 600  | 650  | 750  | 1000 | 1200 | 1500 | 2000 | —    |
| 20                            | 600  | 700  | 800  | 850  | 1000 | 1300 | 1500 | 2000 | —    | —    |

5. Conclusion
Heavy truck is the main type of traffic accident in downhill section. Through the analysis of the running speed characteristics, the relationship between the slope of traffic accident occurrence point, the average slope of the distance before the accident occurrence and the traffic accident rate is obtained. Based on the requirement of effectively reducing vehicle running speed and the braking performance curve of downhill section of dominant vehicle type, the recommended index values of continuous downhill gentle
slope gradient and slope length are put forward, which can be used as reference for designers in design.

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