DESIGN METHODS FOR SAFETY ENHANCEMENT MEASURES ON LONG STEEP DOWNGRADES

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ABSTRACT
Restricted by the rolling terrains of mountainous areas in western parts of China, long steep downgrades are very common in mountainous freeways. Influenced by the factors like high altitude, big elevation differences, and the severe weather condition e.g. black ice, heavy snow and thick fog, most long steep downgrades turn to traffic accident prone sites. Moreover, once traffic accident happens, the severity is high and the society influence is wide. So the overall safety level of mountainous freeways has been greatly influenced by the safety level of long steep downgrades. In this paper, the safety classification methods and the general design principles of long steep downgrades and the design principles of safety enhancement measures for different sections of long steep downgrades are put forward based on the investigation of typical long steep downgrades in freeways. Then the methods for the safety enhancement measures design on long steep downgrades according to the safety level are expounded. Moreover, the design process of the safety enhancement measures design is presented. The presented research finding provides an important support for the safety enhancement measures design on long steep downgrades.

1 INTRODUCTION
With fast growing of the construction of freeway in China, the mileage of mountainous freeway has greatly increased. For the limitation of the terrain, road environment and investment of the project etc., long steep downgrades (LSD) is often used in mountainous freeway design. LSDs are easy to be seen in freeways in many western provinces of China, e.g. Sichuan, Yunnan, Guangdong, Hubei, Fujian, and Shanxi. The maximum length of existing LSD has already been over 50km, and the average grade amounts to 3 percent. The typical characteristics of LSD are the continuous elevation reduction and the steep grades. Influenced by factors such as high altitude, big elevation differences, severe weather conditions like
heavy snow, black ice, thick fog etc. are common in those areas. So the service level of LSD is relatively low, and most LSDs turn to traffic accident prone sites. Once traffic accident happens, the severity is high and the society influence is wide. Moreover huge economic losses would be made and highway management departments would be under huge pressures. Under the severe situation, highway management departments work hard to implement safety improvements from the aspects of traffic engineering and operation management with traffic accident data to reduce the possibility and severity of the accidents as much as possible.

Much research has been conducted on safety enhancement techniques on LSD. The project Research on the safety enhancement techniques on long steep downgrades (Chang’an University, 2007) put forward safety enhancement countermeasures setup suggestions on typical segments of LSD. Zhou, Tang et al. (2009) has discussed traffic safety countermeasures on LSD from the aspects of geometric design and safety facilities. Liang (2009) has set up an evaluation index system of traffic safety facilities and fuzzy comprehensive evaluation methods based on AHP. Xiao (2009) put forward the traffic safety enhancement design concepts, principles and methods from the view of sight induction, visual warning, forced deceleration and emergency relief. Zhou, Yang et al. (2010) summarized the design methods of safety enhancement system on LSD from the angle of geometric design, general design of safety facilities. Xiong (2011) put forward the general countermeasures and the experience of traffic safety treatment on LSD with demonstration projects.

Though much existing research has dealt with traffic engineering safety enhancement measures on LSD, few of them referred to the principles and methods of safety enhancement measures design. Meanwhile, road environment characteristics and vehicles operation characteristics have not been considered yet. Based on the site investigation on typical LSD in mountainous freeways, this paper aims to put forward the detail safety enhancement measures according to the safety level of LSD as well as the design principles, design methods and design process, so as to provide technical support for the safety enhancement design.

2 SAFETY LEVEL CLASSIFICATION METHODS BASED ON TRUCK BRAKE TEMPERATURE

To control the operating speed of trucks on LSD, brakes are frequently used, so the brake temperature keeps rising. The sharp reduction or the failure of braking performance always contributes to traffic accidents. For the vehicle characteristics, overloading and bad driving behaviors such as over speed and neutral taxiing, 60–80 percent of traffic accidents on LSD deal with trucks. According to the statistical results of accidents, the most common traffic accident types on LSD are rear end and run away caused by the failure of braking performance. So the operation safety requirement of heavy-duty trucks should be firstly and fully considered in the safety enhancement measures design on LSD.

From the above analysis, braking performance of heavy-duty trucks is closely related to traffic safety. So the change of brake temperature of trucks on LSD should be analyzed first in order to determine the traffic safety level of LSD. Currently, the most frequently used prediction model of brake temperature is developed by Americans on the basis of theoretical analysis and field experiments. The model (PIARC, 2003) is shown in following equations (in English units).

\[ T(t) = (T_e \times e^{kt}) + T_o \times (1 - e^{-kt}) + k2 \times P^b \times (1 - e^{-kt}) \]

where:
$T_i =$ initial brake temperature (suggested default value: 150° F)

$T_a =$ ambient temperature (suggested default value: 90° F)

$k_1 = 1.23 + 0.0256 \times V$

$k_2 = 0.1 + 0.00208 \times V$

$P_B =$ braking power (hp)

and:

$P_B = P_G - P_E - P_F$

$P_G =$ grade power (hp)

$P_E =$ engine braking power (hp) (default value is 73 hp)

$P_F =$ friction power (hp)

$P_G = \frac{W \times G \times V}{375}$

$P_F = \frac{(450 + 17.25 \times V) \times V}{375}$

where:

$W =$ weight of vehicle (lbs)

$G =$ grade percent (%)

$V =$ speed (mph)

For convenience, PIARC distributed computing software in road safety manual to calculate the brake temperature of trucks on LSD. Given the parameters such as profile data of LSD, the mass and the number of axis of the truck, operating speed, the brake temperature of the truck on each point of LSD could be automatically calculated. With these calculated brake temperature, the safety level of LSD can be determined to provide support for scientifically determining the safety enhancement measures on LSD.

**Figure 1: Brake temperature calculation software for trucks**

Experiments results implemented by Zhou Ronggui et al. from Research Institute of Highway show that when the brake temperature is below 200 °C, the operation status is safe; when the brake temperature is between 200 and 300 °C, the operation status is moderate safe;
when the brake temperature over 300℃, the operation status is unsafe. According to the research findings presented by Chang’an university, when brake temperature rises to 290℃, only 66% of the brake performance is remained, and the brake distance is 1.67 times bigger than normal. So 290℃ is recommended as the critical brake temperature. Research done by American recommend 260℃ as the critical brake temperature. Research results done by France show that operation risks appears when the brake temperature exceeds 200℃. Considering above research findings and the characteristics of domestic vehicles, 200℃, 260℃ and 300℃ are recommended as the safety temperature, critical temperature and failure temperature of brakes of trucks respectively in this paper. With these critical values of brake temperature, safety level of LSD can be determined as shown in table 1.

<table>
<thead>
<tr>
<th>Safety level</th>
<th>Brake temperature T (℃)</th>
<th>Safety description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level I</td>
<td>T≤200</td>
<td>Good</td>
</tr>
<tr>
<td>Level II</td>
<td>200&lt;T≤260</td>
<td>Fair</td>
</tr>
<tr>
<td>Level III</td>
<td>260&lt;T≤300</td>
<td>Poor</td>
</tr>
<tr>
<td>Level IV</td>
<td>T&gt;300</td>
<td>Dangerous</td>
</tr>
</tbody>
</table>

When the safety level is level I, vehicles run freely on LSD, and few braking is needed. The operation status of vehicles is good.

When the safety level is level II, vehicles run freely on LSD, and braking is needed occasionally. The brake temperature is between 200℃ and 260℃. The operation status of vehicles is fair.

When the safety level is level III, vehicles run freely on the segments near the beginning of the LSD. With the increase of the distance to the beginning of LSD, the operating speed grows faster and faster. Braking is commonly used to control the operating speed. The brake temperature is between 260℃ and 300℃. The operation status of vehicles is poor.

When the safety level is level IV, vehicles run freely on the segments near the beginning of the LSD. With the increase of the distance to the beginning of LSD, the operating speed grows faster and faster. Braking should be frequently used to control the operating speed. The brake temperature is over 300℃. The brake performance decrease severely and couldn’t meet the requirement of safety operation. The operation status of vehicles is dangerous.

3 GENERAL DESIGN PRINCIPLES FOR SAFETY ENHANCEMENT MEASURES

Main safety enhancement measures on LSD can be classified into three types, active safety measures, passive safety measures and traffic management measures. Active safety measures aim to avoid traffic accidents through strengthening communication between road environment and drivers by such measures as active prompt and guidance. Passive safety measures are always used to alleviate the severity of traffic accidents and reduce the losses of traffic accidents. In the design and management of LSD, active safety measures should be given the priority to other measures to avoid traffic accidents happening. Then passive safety measures should be used to reduce the fatalities and economic losses caused by traffic accident. Meanwhile, related traffic management measures should be used to restrict driving behaviors as well as to assure the effects of engineering measures.
Considering traffic safety hazards such as special road environments, severe natural environments, driving behaviors of domestic drivers and the vehicle performance of domestic trucks, the systems engineering concept should be used in the design of LSD. From the view of operation safety, LSD should be considered as a sub-system from the phase of geometric design to the phase of traffic engineering design. Operation safety requirements in both time dimension and spatial dimension should be fully considered in the design of LSD. And multidimension integration design methods should be used for the system safety on LSD. In time dimension, the safety requirements in short term and long term should be both considered. In spatial dimension, safety requirements in heading direction of the vehicle, transverse and profile of the segments and the coordination of facilities in different spatial positions should be considered.

4 DESIGN METHODS FOR SAFETY ENHANCEMENT MEASURES

From the angle of operation safety requirements, any LSD system can be classified into 4 sections (shown in figure 2), i.e. upstream of the beginning of the downgrade, the beginning of the downgrade, the downgrade section and the end of the downgrade. The design principles of safety enhancement measures in different sections of LSD system are shown in table 2.

Figure 2: Section classification of LSD system based on safety enhancement measures
Table 2: Design principles of safety enhancement measures in different parts of LSD

<table>
<thead>
<tr>
<th>Sections</th>
<th>Operational safety requirements</th>
<th>Types of measures</th>
<th>Examples of measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream of the beginning of the downgrade</td>
<td>Forecast of the downgrades ahead, e.g. the length and the average grade of LSD.</td>
<td>General measures</td>
<td>Setting traffic signs like warning signs of LSD and service facilities forecast signs etc.</td>
</tr>
<tr>
<td>The beginning of the downgrade</td>
<td>The announcement of the beginning of the downgrade</td>
<td>General measures</td>
<td>Setting traffic signs like the beginning of the LSD, using low gear, 3rd gear for heavy-duty trucks, speed limitation signs and overtaking prohibited signs etc.</td>
</tr>
<tr>
<td>The downgrade section</td>
<td>Operation safety reminding and safety protection</td>
<td>Special measures</td>
<td>Detail safety measures depends on the safety level of the section</td>
</tr>
<tr>
<td>the end of the downgrade</td>
<td>Conformation of the end of the downgrade, and the forecast of principal structures and the geometric alignment ahead.</td>
<td>General measures</td>
<td>Setting traffic sign like the end of the downgrade signs, forecasting signs of off-ramps, tunnels, and segments with poor geometric alignment ahead etc.</td>
</tr>
</tbody>
</table>

The downgrade section is the most important part in LSD system. The safety level of this section has an effect on the overall safety level of the LSD system. And the safety requirements of vehicles running in this section are the highest. So the safety enhancement measures design for this section is critical important. Considering the road characteristics, traffic characteristics, safety requirements of heavy-duty trucks and the safety level classification results, safety enhancement measures design principles on the downgrade section are as follows.

(1) Design principles on Level I section
If the safety level of LSD system is level I, the brake temperature of heavy-duty trucks is below 200°C. The possibility of traffic accidents occurring caused by high brake temperature is relatively low. The safety level of the LSD system is good. The design methods for safety enhancement measures used in other segments of the road are suitable for this situation.

(2) Design principles on Level II section
If the safety level of LSD system is level II, the brake temperature of heavy-duty trucks is over 200°C but lower than 260°C. The possibility of traffic accidents occurring caused by high brake temperature is low. The safety level of the LSD system is fair. The safety requirements of heavy-duty trucks should be emphasized, and the safety protection level should be increased. To avoid traffic accidents caused by high brake temperature, active safety engineering measures should be considered first to enhance the ability of active guidance and operation safety reminding.

(3) Design principles on Level III section
If the safety level of LSD system is level III, the brake temperature of heavy-duty trucks is over 260°C but less than 300°C. The braking performance of trucks declines in some sense. The possibility of traffic accidents occurring caused by high brake temperature is high. The safety level of the LSD system is poor. Safety requirements as well as operation management of heavy-duty trucks should be both emphasized. Considering the high possibility of trucks’ out of control, active safety engineering measures and passive protection safety engineering measures should be both used. In addition to the active guidance and operation safety reminding, passive protection for trucks should be emphasized to reduce the severity and the losses of traffic accidents.

(4) Design principles on Level IV section

If the safety level of LSD system is level IV, the brake temperature of heavy-duty trucks is over 300°C. The braking performance of trucks declines sharply. The possibility of occurring traffic accidents caused by high brake temperature is extremely high. The safety level of the LSD system is very poor. The safety requirements and operation management of heavy-duty trucks should be fully considered in safety enhancement measures design. Considering the extremely high possibility of trucks’ out of control, comprehensive safety countermeasures should be emphasized in addition to active and passive safety engineering measures. With supporting traffic management measures, the expected protection effects of safety engineering measures can be assured. Moreover, driving behaviors of truck drivers and the drivers’ route selection can be intervened through the corporation of multi traffic management departments to eliminate hidden traffic accident hazards and avoid bringing into the LSD system. Then the severity and the losses of traffic accidents on LSD system could be reduced.

5 DESIGN PROCESS FOR SAFETY ENHANCEMENT MEASURES

According to the safety level classification methods and safety enhancement measures design methods, process of safety enhancement measures design is as follows, shown in figure 3.
Figure 3: Design process of safety enhancement measures design on LSD

1. Extracting LSD with profile design data and corresponding standards and specifications.
2. Determining parameters such as typical type of trucks, axis, and gross weight and operating speed with investigation results of existing roads or similar roads in current road network.
3. Calculating brake temperature of trucks with parameters extracted from investigation results, analyzing the variations, and determining safety level of LSD according to the brake temperature of trucks at the end of the downgrade.
4. Determining safety enhancement measures types for special points and segments of LSD such as the upstream of the beginning of the downgrade, the beginning of the downgrade, the downgrade section, the end of the downgrade with safety level analysis results.
5. Considering the factors such as the terrain characteristics and the weather condition, determining active safety, passive safety and traffic management measures based on the general design principles and design methods presented in this paper.
6. Considering the characteristics of different types of traffic engineering measures and the coordination and consistence requirements, determining setting locations and detail design.
parameters of safety enhancement measures and putting forward recommendations of traffic management countermeasures.

6 CONCLUSIONS
This paper presents safety level classification methods for LSD system based on the brake temperature of trucks, and this system can be classified into four sections, the upstream of the beginning of the downgrade, the beginning of the downgrade, the downgrade section and the end of the downgrade from the view of traffic safety. Then the general design principles of multi-dimension integration design, and the characteristics of safety enhancement measures design on different parts of LSD system is put forward. Finally, the safety enhancement measures design methods for different safety level of the LSD system and the design process is presented. It is proved that the research findings has provided technical support for both the safety enhancement measures design for new constructed LSD and the safety improvements for existing LSD, and is of great importance for the safety level improvement of LSD system.

REFERENCES