Safety Performance Evaluation Method of Horizontal Curve on Freeway Based on Driving Workload

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Abstract

Evaluating the horizontal curve indices performance of freeways is important to developing an understanding of impact to driver safety and comfort. Based on the well-established theory and measurement of driving workload, typical vehicles (include passenger car and truck) were chosen for field driving test with randomly samples of 28 driver. In this research we analyzed the 652 horizontal curve sections being selected on road section with r (radius of horizontal curve) ranging from 125~1400m and i (longitudinal slope) ranging from -6~6%. Using a multiple regression model we established that there is a measurable and statistically significant increase in driving workload degree as horizontal curve radius decreases. We believe that we have developed a model that takes into account driving workload and horizontal curve indices of mountainous freeway with the applicability to designs and managements.

Keywords: driving workload; horizontal curve; driver safety and comfort; safe performance evaluation

Introduction

Horizontal curve is an important part of the road alignment, including the circular curve and transition curve. Radius and length of horizontal curve are closely related to road safety. The minimum radius and length of horizontal curve are regulated by the Chinese “Design Specification for Highway Alignment” (“Specification” for short) and the values are in Table 1. All the values are main calculated using the automobile driving mechanics theory, whether it can meet the demand of driver's driving comfort or not still need further quantizing verification. Novizentsev B.B, The former Soviet Union, studied the relationship between pulse, dermal electric, curve radius and driver emotion (Новизенцев В.В. 1977). Heger, R, Germany, studied relationship between road alignment and driver’s psychology and physiology (Heger, R. 1998). Bong-Jo CHUNG, Korea, studied that psychological and physiological signals of EEG, ECG, EOG can be used to evaluate the road safety. (Bong-Jo CHUNG, Jae-Beom PARK, Ju-Young KIM, etc. 2003). PAN Xiaodong, ZHENG Ke, ZHAO Liang and many other scholars studied safety of horizontal curve by using driver's heart rate, blood pressure, rate of pupil changes, heart rate variability and some other psychological and physiological indices and verified the feasibility of horizontal curve safety evaluation by using psychological and physiological indices (PAN Xiaodong, DU Zhigang, JIANG Hong etc.2006; Zheng Ke, Rong Jian; ZHAO Liang. 2008).
But there are still two unsolved problems: (1) Study results cannot achieve better engineering applications; (2) Individual difference of driver psychological and physiological is not eliminated. During these years these two problems have been solved using driving workload degree measurement method and calculation model by my research team.

<table>
<thead>
<tr>
<th>Table 1 Horizontal curve alignment indices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design speed (km/h)</td>
</tr>
<tr>
<td>Minimum radius of circular curve (m)</td>
</tr>
<tr>
<td>general value</td>
</tr>
<tr>
<td>limited value</td>
</tr>
<tr>
<td>Minimum length of horizontal curve (m)</td>
</tr>
<tr>
<td>general value</td>
</tr>
<tr>
<td>limited value</td>
</tr>
</tbody>
</table>

We established a theory and measurement of driving workload, when driving on a road; the frequency and nature of the tasks that road, traffic, and environmental conditions impose on the driver determine the amount of input to the information channel supporting work under the pressure. In this study, driving workload mainly refers to the driver’s mental workload. To remove individual differences between drivers and to reflect the impact of speed on driving workload, we used driver real-time $\frac{LF}{HF}$ changes per unit speed as an analytical index of driving workload. The calculation model is as follows (1):

$$K_{ij} = \frac{\left(\frac{LF}{HF}\right)_{ij} - A_i}{V_{ij}}$$

Note:

$K_{ij}$ —— driving workload degree while driver $i$ driving on the $j$ position;

$LF_{ij}$ —— Low frequency while driver $i$ driving on the $j$ position (ms$^2$);

$HF_{ij}$ —— High frequency while driver $i$ driving on the $j$ position (ms$^2$);

$A_i$ —— $\frac{LF}{HF}$ while driver $i$ driving normally;

$V_{ij}$ —— operation speed while driver $i$ driving on the $j$ position (km/h).

Moreover, we divided road safety levels into 3 by classification of driving workload degree, the classification thresholds are given in Table 2.
Table 2 Driving comfort threshold of driving workload degree

<table>
<thead>
<tr>
<th>Road safety level</th>
<th>Indices threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cars</td>
</tr>
<tr>
<td>Higher risk</td>
<td>$K &gt; 0.060$</td>
</tr>
<tr>
<td>High risk</td>
<td>$0.030 &lt; K \leq 0.06$</td>
</tr>
<tr>
<td>Safety</td>
<td>$-0.001 &lt; K \leq 0.030$</td>
</tr>
</tbody>
</table>

In order to research on the safety performance evaluation method of horizontal curve on mountain freeway, it is necessary to define the basic horizontal curve section based on driving workload and analyses the correlation between driver comfort and safety and horizontal curve indices.

**Test scheme**

(1) Test object
In order to define the condition of basic horizontal curve section based on driving workload and analyses the correlation between driver comfort and horizontal curve indices.

(2) Test content
14 passenger car drivers and 14 truck drivers were selected driving on test sections and collected driving workload degrees under different horizontal curve index and operation speed.

(3) Test road
Operation speed is adopted to evaluate alignment safety in Chinese “Guidelines for Safety Audit of Highway” (“Guidelines” for short). Defined horizontal curve is a basic road section with horizontal curve radius less than 1000m, and longitudinal slope less than 3% (Ministry of Transport of the People’s Republic of China. Guidelines for Safety Audit of Highway 2004).
According to the regulation of horizontal curve and longitudinal slop indices in “Specification”, we confirm critical basic horizontal curve section which is comfort for driving fluctuates in $r=1000m$ and $i=3\%$. Take mountainous freeway sections (more horizontal curves are including in this section) with $r \leq 1400m$ and $i \in [-6\%, 6\%]$ as test section.

(4) Tested driver
All tested drivers were selected randomly. They were good healthy, skillful, well-balanced and well-eyesight.

(5) Test instrument
A dynamic GPS, a KF2 dynamic multi-parameter physiology and psychology recorder, and an SMI iViewX HED system were employed for measurement of driving behavior and driving workload, as shown in Figure1 (a), (b) and (c).
KF2 (Fig1.(a)) was adapted to record the tested drivers’ physiology and psychology parameters, including test time, high-frequency (HF, 0.15–0.40 Hz), low-frequency (LF 0.04–0.15 Hz). Collected frequency is 250HZ and error less than 3 times per minute. Continuous real-time record is more than 24h. GPS (Fig1.(b)) was used to record test time, distance, speed, and three-dimensional position throughout the experiments. Collected frequency is 10HZ, speed precision is 0.03m/s and error of three-dimensional position is less than 0.45m. SMI iViewX HED eye tracker system (Fig1.(c)) is used to record interesting fixation point while driving and test time. The eye tracker is used to eliminate factors but not alignment effecting on driver's physiology and psychology, such as vehicles and obstacle in the road system. Collected frequency is 50HZ, capture area of horizontal direction is ±30, and vertical direction is ±25.

(6) Experimentation method
Operation speed, position and driving workload were collected on one-way two-lane mountainous freeway, with free flow and good weather condition. The experiment processes consist of three steps, including equipment installation, data collection (include static and driving). The operational procedures in detail areas follow:
Instrumentation installation: Prior to the test, the drivers were given a questionnaire addressing such issues as local or outsider, driver health, driving experience, age, non-professional or professional, and so on; dynamic GPS, eye tracker and KF2 were equipped. Static collection: collected driving workload in an un-driving state by KF2.
Driving collection: operation speed, spatial position and driving workload were collecting while driving. Driver speaking, smoking, calling, uncomfortable and unsafe or bad behavior were
recorded in real-time in to verify the reliability of data.
Finally, samples of 351 section of passenger cars and 301 sections of trucks were collected in tests.

**Definition of basic horizontal curve section**

Analyzing orderliness of driving workload degree of cars and trucks, it is concluded that: when cars driving at the longitudinal slope \( i \in [-3\%, 3.5\%] \), the driving workload degree is unaffected by longitudinal slope; when trucks driving at the longitudinal slope \( i \in [-3\%, 2.5\%] \), the driving workload degree is unaffected by longitudinal slope, as shown in Table 3.

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Longitudinal slope ( i ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cars</td>
<td>(-3 \leq i \leq 3.5)</td>
</tr>
<tr>
<td>Trucks</td>
<td>(-3 \leq i \leq 2.5)</td>
</tr>
</tbody>
</table>

Analyzing orderliness of driving workload degree of cars and trucks on horizontal curve, it is concluded that:

(1) Cars
When \( r \in [170m, 260m] \), the driving workload degree changing is inconsistent; when \( r \in [260m, 850m] \), the driving workload degree appear consistent variation, that the driving workload degree decreased in a acceptable range(Figure 2 (a)); When \( r \geq 850m \), the driving workload degree first increased and then decreasing, and the peak locates near point of spiral to tangent (ST).
Therefore, 260m was taken as the critical value of minimum radius and general radius of horizontal curve, 850m was taken as the critical value of general radius and large radius of horizontal curve or straight line.

(2) Trucks
When \( r \in [170m, 380m) \), the driving workload degree changing is inconsistent; when \( r \in [380m, 930m] \), the driving workload degree appear consistent variation, first increased and then decreasing in a acceptable range(Figure 2 (b)) ; when \( r \geq 930m \), the driving workload degree is invariable.
Therefore, 380m was taken as the critical value of minimum radius and general radius of horizontal curve, 930m was taken as the critical value of general radius and large radius of horizontal curve or straight line.

![Figure 2 The trends of driving workload Degree](image)

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5
In summary, horizontal curve is defined as shown in Table 4.

<table>
<thead>
<tr>
<th>Index</th>
<th>Car</th>
<th>Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal slope (°)</td>
<td>(-3 \leq i \leq 3.5)</td>
<td>(-3 \leq i \leq 2.5)</td>
</tr>
<tr>
<td>Radius of horizontal curve (m)</td>
<td>(r &lt; 850)</td>
<td>(r &lt; 930)</td>
</tr>
</tbody>
</table>

### Establishment of safety performance evaluation model

Selecting Eigen value

When horizontal curve is appearing, drivers began to adjust driving behavior in order to ensure the comfort of driving. So driving workload degree changes ahead of a basic alignment section. Considering orderliness of driving workload degree on different the radius of horizontal curve we discussed at chapter 3, Eigen value is selected as follows:

1. **Cars**
   - When \(r < 260\) m, the eigen value is the average of driving workload degree where range from sight distance ahead of to end-point of horizontal curve.
   - When \(260 \leq r \leq 850\) m, the eigen value is the average of driving workload degree in sight distance ahead of horizontal curve.

2. **Trucks**
   - When \(r < 380\) m, the eigenvalue is the average of driving workload degree where range from sight distance ahead of to end-point of horizontal curve.
   - When \(380 \leq r \leq 930\) m, the eigen value is the average of driving workload degree in sight distance ahead of horizontal curve.

We obtained the eigen value of cars and trucks as shown in Table 5 and Table 6. (Due to limited space, the only listed three groups).

### Table 5 Test car samples

<table>
<thead>
<tr>
<th>Number</th>
<th>Radius of horizontal curve (m)</th>
<th>Length of Horizontal curve (m)</th>
<th>Length of Transition Curve (m)</th>
<th>Driving workload Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>170</td>
<td>308</td>
<td>70</td>
<td>0.060129</td>
</tr>
<tr>
<td>2</td>
<td>210</td>
<td>245</td>
<td>80</td>
<td>0.072053</td>
</tr>
<tr>
<td>3</td>
<td>252</td>
<td>258</td>
<td>80</td>
<td>0.049184</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

### Table 6 Test truck samples

<table>
<thead>
<tr>
<th>Number</th>
<th>Radius of horizontal curve (m)</th>
<th>Length of Horizontal curve (m)</th>
<th>Length of Transition Curve (m)</th>
<th>Driving workload Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>210</td>
<td>245</td>
<td>80</td>
<td>0.049862</td>
</tr>
<tr>
<td>2</td>
<td>225</td>
<td>189</td>
<td>60</td>
<td>0.041104</td>
</tr>
<tr>
<td>3</td>
<td>230</td>
<td>191</td>
<td>60</td>
<td>0.046205</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
There are some factors such as the alignment before horizontal curve, length of transition curve, radius of horizontal curve and, length of horizontal curve affecting driving workload degree, so we should know which is relate to driving workload degree.

By Partial relativity and scatter plot, it is obtained that except for length of horizontal curve (only for truck) and radius of horizontal curve; other factors have no significant relationship with driving workload degree.

The scatter plots of relationship between workload degree and each influencing factor are as shown in Figure 3(a), (b), (c) and (d).
Using the SPSS13.0, we established models for car and truck, as shown in equation (1) and (2).

$$K = 39.151 \times R^{1.22}$$

(1)

$$K = \frac{7.616}{R} + \frac{6.489}{L} - 0.019$$

(2)

Where: $K$—driving workload degree;
$r$—the Radius of Horizontal Curve, Unit: m;
$L$—the Length of Horizontal Curve, Unit: m.

**Model Application:**
- *Car* $V \leq 90$Km/h, $r \in [125m, 850m]$.
- *Truck* $V \leq 60$Km/h, $r \in [125m, 930m]$.

Passenger Car: $R^2 = 0.692, F = 67.38 \geq F_{0.05}(1, 30) = 4.17$
Truck: $R^2 = 0.647, F = 20.144 \geq F_{0.05}(2, 22) = 3.44$

By further analysis of residual, the models are well-fitting.

### Safety analysis of horizontal curve

According to the model and driving comfort threshold of driving workload degree, we analyzed the safety performance of horizontal curve.

1. **For car**
   - Take $K = 0.060$ (critical between higher risk and high risk) into model (2), it is obtained that $r = 203m$;
   - Take $K = 0.030$ (critical between high risk and safe risk) into model (2), it is obtained that $r = 358m$. That is when radius of horizontal curve $r < 203m$, it is higher risk road sections; when radius of horizontal curve $r \in [203m, 358m)$, it is high risk road section; when radius of horizontal curve $r \geq 358m$, it is safe road section.

2. **For truck**
   - Take $K = 0.070$ (critical between higher risk and high risk) and $K = 0.035$ (critical between high risk and safe risk) into model (3), it is obtained that when $7.616/r + 6.489/L > 0.07$, it is higher risk road section; when $0.035 < 7.616/r + 6.489 \leq 0.07$, it is high risk road section; when $7.616/R + 6.489/L \leq 0.035$, it is safe road section.

The models are adopted to evaluate the safety performance of horizontal curves on two mountainous freeways in China, with one way two-lane. Higher risk and high risk road sections are obtained by inputting indices of horizontal curves into the models. According to accident data in three years on both roads, 72% of car accidents and 66.7% of truck accidents occurred on both higher risk and high risk road sections we defined. So the models can be evaluated the safety performance of horizontal curves well. If we determine the higher risk and high risk road sections according to models, some measures should be taken to reduce the risk.

### Conclusion

Based on the well-established theory and measurement of driving workload, we redefined basic horizontal curve section, as shown in Table 7.
Moreover, we have developed two models to evaluate the safety of horizontal curves and it has been verified by accident data of two mountainous freeways. It useful to determine the higher risk and high horizontal curve sections on mountainous freeways. For one hand, it can verify the design rationality of horizontal curve. For the other hand, it can provide supervisor with road operation risk information and supervisor depends on the information can take measures to reduce the risk.

We believe that we have developed these models that take into account driving workload and horizontal curve indices of freeways with the applicability to future designs and managements.

**Acknowledgments**

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