RESEARCH ON COMFORT AND SAFETY THRESHOLD OF THE PAVEMENT ROUGHNESS

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ABSTRACT

Pavement roughness, which may cause vehicle vibrations and driving instability even out of control, is the
main cause of unsafety and discomfort of driving. In most countries, while evaluating the pavement
operation quality, international roughness index (IRI) is used to measure the pavement roughness.
Currently, the driving comfort and safety is valued by empirical method of expert scoring, while reliable
experimental measurements are not created. Based on our previous work, which included evaluation of
driving comfort and safety (driving workload) by physiological and psychological indexes, and threshold
of the driving comfort and safety, in this article we determine the mathematical relationship between IRI
and driving workload with experimental data of real vehicles to study the threshold of IRI for driving
comfort and safety. Experimental data, including physiological and psychological indexes, driving speed,
and IRI, of 12 car drivers and 12 truck drivers driving at speed of 60 km/h, were collected on a road with
high alignment elements that had no impact on driving workload, in the northwest of China. The
mathematical relationships between IRI and driving workload of car drivers and truck drivers were
determined, and thresholds of IRI on road segments at different risk levels for driving comfort and safety
were obtained. Our results show the standard IRI values for pavement maintenance in China are beyond
the comfort and safety thresholds for both car drivers and truck drivers. Methods and conclusions in this
article could provide theoretical and technical support for the improvement of pavement service.

Key words: pavement engineering; pavement roughness; driving safety and comfort; driver’s
driving workload
FOREWORD

Pavement roughness is one of the important pavement performances affecting driving safety, stability, comfort and transporting efficiency. In evaluating the indicators of Pavement Quality or Performance Index (PQI) in China, the weight of the Riding Quality Index (RQI) which is affected by roughness is 0.4(1). Roughness $\sigma$ is an important index in Maintenance Control Index (MCI) in Japan. The dispersion degree index of the longitudinal roughness of the wheel track is also one of the important indexes of Present Serviceability Index (PSI) established by AASTHO (2). The PSI is changed to Riding Comfort Index (RCI) in Canada and the direct relationship between RCI and pavement roughness is built (3). We can see the significance of pavement roughness. Thus, it is an urgent task for road engineering construction and management to ensure riving safety, stability and comfort and also to quantify these factors in an objective and accurate method.

Up to now, IRI is the most widely used index in roughness evaluation. But the standard values are different in Spain, Sweden (4), United States (5) and other countries. From the Seventh Five-Year Plan, IRI has been used as an indicator for pavement roughness in pavement management in China (6). Present technical specification of maintenance stipulates the maximum value of IRI: the IRI of Expressway asphalt pavement $\leq 6m/km$ (7) and that of cement concrete pavement of Expressway $\leq 4.2m/km$ (8). In earlier period, IRI threshold was determined by the scores given by the experts, who evaluated the road section-by-section based on their experience (9), therefore, the results lacked objectivity and reliability. Tehrani established IRI threshold values for good, fair, and poor road condition based on public perception using the method of questionnaire and psychometric scaling analysis (10). Some scholars evaluated pavement roughness, safety and comfort based on the quantitative classification of effects on human comfort set forth in 《the evaluation of mechanical vibration and human exposure to whole-body vibration》 (GB/T 13441.1-2007/ISO 2631-1:1997) (11). According to the above quantitative standard, Zengli Gao (12) has proposed the quantitative index of passenger discomfort and established model of the relationship between subjective quantitative weighted averages and pavement roughness standard deviation. Wanqiao Yang (6) used the root mean square of weighed acceleration relating to vehicle vibration as the evaluation index of human vibration comfort in the appraisal of asphalt pavement roughness and made evaluation according to the relationship between root mean square values of weighted acceleration in the provisions of the international standard ISO 2631. Shuyun Wang (13) established the root mean square of weighed acceleration and IRI linear regression model, choosing criteria for riding comfort in the ISO2631 to evaluate asphalt pavement roughness IRI, and to define the IRI comfort threshold. Based on the relationship between the root mean square of weighed acceleration and the comfort level of human, Feng Wang (14) studied the relationship between the acceleration under different friction coefficient, different roughness, different speed and the subjective feelings of the human body. He made statistical analysis on large amounts of data which measured from asphalt concrete road on the outdoor ordinary road and indoor driving simulation chamber, and gave the relationship between the maximum driving speed and the pavement roughness under satisfying riding comfort conditions. Jinxie Zhang (15) studied the relationship between riding comfort and pavement roughness from the point of the users, and then proposed the critical value of roughness based on the passengers’ comfort, using passengers’ ECG indexes root mean square of the squared differences of successive n-n intervals (RMSSD) as the main basis for evaluation and combining with subjective scoring method and vibration acceleration evaluation method. Xueru Wang (3) studied the evaluation of the highway asphalt pavement roughness from the perspective of passenger’s comfort. She, respectively selected kilometers and twenty meters as the evaluation unit, and the ECG indexes and vibration acceleration as evaluation basis to extend her research from both the
overall and local angles. In the road transport system composed of drivers, cars, roads and
environment, the core is the driver, whose psychological and physiological state changes
come with the coordination with all parts. In recent years, more and more researchers have
studied driving safety, comfort and driving fatigue from the level of drivers’ physiology and
psychology and to evaluate the rationality and security of the design of commented lines,
pavement and road lighting. With the development of dynamic measuring technology, driving
psychological and physiological indicators can be quantified at the present stage and
pavement roughness can be objectively assessed. Researchers adopt the driver’s
electroencephalograph (EEG), electrocardiograph (ECG) and other physiological and
psychological indicators in the evaluation of pavement roughness and objectively describe
the riding quality. Some scholars use EEG responses to characterize the pavement users’
feeling towards pavement condition; Andreas Sonnleitner studied the relationship between
the driving task quantity and the alpha brain waves (17); Samuel Charlton studied the
relationship between driver's pupil size and blink time and the linear index of the road (18);
Thomas Kübler studied the changes of the driver's ECG index in the emergent event
(19); Some scholars used EEG to describe the influence of pavement roughness on the
driver’s physiology and psychology (20). Qiuyun Mo studied the relationship between the
driver's ECG index and the longitudinal slope of the road (21); Jiangbi Hu and Xiangzheng
Chang used the driver's driving workload to evaluate the road alignment index (22); Wei
Yuan chose four kinds of ECG data to characterize the driver's workload (23). However,
many researches from the angle of the driver’s physiology and psychology were limited to
qualitative and partially quantitative description, lacking of systematic quantitative evaluation
method.

Based on the above analysis, this paper has made contribution in the following aspects:
Put forward driver's safety and comfort driving workload theory, quantitative evaluation
method of load degree and the driver’s safety comfort classification threshold; Study the
relationship between driving workload and road roughness from the perspective of driver’s
physiology and psychology, by adopting the advanced dynamic test method; Determine the
pavement roughness threshold based on driving safety and comfort workload; And provide
theory, method and technical basis for objectively and quantitatively evaluating the safety and
comfort of pavement roughness.

THE INTERACTIVE RELATIONSHIP BETWEEN PAVEMENT ROUGHNESS AND
DRIVING SAFETY AND COMFORT

Pavement roughness is an important performance factor in affecting driving stability, comfort
and safety, and in determining the efficiency of road transportation. Uneven pavement makes
the wheel to vibrate in a certain frequency and amplitude on the road, posing external forces
to the pavement and therefore leading pavement to vibrate accordingly, which will in turn
react on the vehicle running on the pavement and cause additional vibration from the vehicles.
The car body vibration and response vibration can produce coupled vibration. When the
superimposed vibration reaches certain limit, the car will bump and is very likely to lose
control as the drivers will feel uneasy and cannot steer properly or drastically reduce the
speed. Coupled vibration of the vehicle and the road surface is shown in Figure 1.
The dynamic vibration which the running vehicles produce to the pavement will increase with the increase of the pavement roughness level and the running speed of the vehicle; and at the same time, the dynamic vibration will exacerbate the pavement roughness, further affecting driving stability, comfort and safety. Pavement roughness and changes of vehicle vibration amplitude will promote each other, which will generate significant effect on pavement structure, make drivers feel uncomfortable, cause cargo damage, and tend to potentially threat traffic safety. (25).

In the dynamic road system composed of drivers, cars, roads and environment, pavement input is the change of plane and vertical section, and the output transmits to the driver's body through the tire, suspension, car body and seat, then guides the driver in accordance with the trajectory and speed of their own physical threshold (including uniform velocity, acceleration and deceleration) after a comprehensive reflection of the driver's mental and health motivation. Therefore, drivers drive according to the psychological and physical level they can withstand, which in effect reflects driving safety and comfort given the condition of pavement roughness (26).

Some scholars such as Brookhuis (27), Jiangbi Hu(28), have studied the safety problems in the road engineering using the psychological and physiological index. Research has shown that the fluctuation of heart rate variability (HRV) and the ratio of the heart rate of low frequency to high-frequency (LF / HF) can reflect the strength of sympathetic nerve activity, which can be successfully applied to measure drivers’ driving workload. The higher the driving workload is, the lower the HRV will be, and LF will significantly increase; while HF will decrease. As a result, LF / HF will increase notably and sympathetic nerve excitability will enhance. In order to finish the driving task and maintain working ability, drivers need to spend more energy, thus their driving workload will be higher. If the pavement roughness can satisfy the drivers’ driving demand, driving workload will remain in an acceptable range, and the value of HRV and LF/HF will reflect the driving workload of the drivers when being in a safe and comfortable condition. If the pavement roughness can’t satisfy the driving demand, the drivers will ease the driving problems caused by the pavement condition through self-adjustment, the most common of which is changing the running speed. The World Bank has suggested the appropriate running speed given different levels of IRI.

Drivers adjust the effect of feeling and perception stimulation to avoid driving tension and fatigue by changing the running speed, which is a passive adaptation mode, and the moderating effect will weaken when drives have been driving for a long time. Hence, safe driving cannot be guaranteed by simply adjusting speed. It is risky when drivers drive too fast or too slow, or when their driving workload is too high or too low. From the above reasoning, the real time running speed is the most direct external indicator of driver’s daptation to the pavement roughness. Driver’s psychological and physical changes can closely characterize the influence of pavement roughness on driving safety and comfort in a comprehensive and objective manner.
DRIVING WORKLOAD DEGREE AND THE EXPRESSION OF DRIVING SAFETY AND COMFORT

Through crossing and integrating physiology, psychology, road engineering, traffic engineering and other disciplines and with the reference of theory analysis and lots of indoor and outdoor tests, we found that driving workload is the ability to finish driving tasks when the road and environment condition create mental pressure to the drivers.

Driving workload degree is the driver’s driving workload quantization parameter. The econometric model is as formula (1) (29).

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

Formula: \( K_{ij} \) —— Driving workload degree of driver \( i \) on the position \( j \);

\( \left( \frac{LF}{HF} \right)_{ij} \) —— HRV of driver \( i \) on the position \( j \);

\( A_i \) —— HRV when driver \( i \) is driving normally;

\( V_{ij} \) —— running speed (km/h) when driver \( i \) on the position \( j \).

The threshold of Safety classification of driving workload is shown in table 1 (28).

<table>
<thead>
<tr>
<th>Security Level</th>
<th>Car</th>
<th>Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Driving Workload Degree</td>
<td>Index Threshold</td>
</tr>
<tr>
<td>Highly risky</td>
<td>Highest</td>
<td>( K &gt; 0.060 )</td>
</tr>
<tr>
<td></td>
<td>Lowest</td>
<td>( K \leq 0.012 )</td>
</tr>
<tr>
<td>Relatively risky</td>
<td>Higher</td>
<td>( 0.030 &lt; K \leq 0.060 )</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>(-0.012 &lt; K \leq -0.001)</td>
</tr>
<tr>
<td>Safe</td>
<td>Normal</td>
<td>(-0.001 &lt; K \leq 0.030)</td>
</tr>
</tbody>
</table>

THE TEST SCHEME DESIGN OF THE SAFETY AND COMFORT THRESHOLD ABOUT PAVEMENT ROUGHNESS

We collected the drivers’ driving behavior characteristic parameters when driving on the test road, including the running speed of the vehicle, driver’s driving workload level, as well as obtained the IRI value of test road pavement, to analyze the relationship between driving load degree and IRI as to study the drivers’ safety and comfort demands for the pavement roughness at a certain speed. In order to eliminate the influence of road alignment, traffic and weather conditions on the driving workload, we specially chose the highway in a mountainous area in Northwest China as our test road, which is straight, small in traffic volume, and gentle in slope gradient and paved by cement concrete. In order to eliminate the individual differences and to improve the reliability and consistency of the measurement data, the test on each driver will be repeated 3 times on the same test road.
Tested Drivers and Vehicles

Tested drivers
According to the experimental objective, we selected healthy drivers with normal eyesight and had no history of loin, legs and cardiovascular diseases. Before the test, the drivers should rest well to ensure normal reaction. According to $P(x \geq 1) = 1 - (1 - p)^n$, while $p$ (the probability of producing one kind of driver's driving workload) is 90%, $P$ (the probability that the situation occurs at least once) is 100%, we need at least 6 drivers for each type of car. Based on cognitive psychology theory and taking into account experimental conditions, we selected 24 test drivers (12 test car drivers and 12 test truck drivers) with general level of driving skills to ensure data reliability.

Tested vehicles
The tested cars and trucks were all representative and with considerable service distance, as shown in figure 2.

FIGURE 2 Tested vehicle

Testing Instruments and Equipment

Dynamic Multi-Parameter Physiology Recorder
The test used KF2 dynamic multi-parameter physiology. The acquired instrument data was 60 times /min, the error was less than 3 times /min and the real time continuous test was greater than 24 hours. The KF2 recorder was adapted to record the driver’s physiology and psychology parameters, including heart rate, respiration, body position (body movement) and surface temperature, as shown in figure 3(a).

Dynamic Eye Tracker
The SMI iView X 1.05 build 49 HED (produced by Senso Motoric Instruments) was used to dynamically record road environment information and driver’s fixation point, pupil diameter and other information in the driver’s vision. The screen resolution is 768*576 pixels; the data acquisition frequency is 50 Hz; horizontal eye movements catch range is ±30°, vertical direction is ±25°; eye tracking resolution is 0.1°; eye focus accuracy is 0.5°-1.0°, as shown in figure 3(b).
The Novatel Dynamic GPS was used to locate the vehicles’ movement. The acquisition frequency is 10 Hz; operating speed precision is 0.03m/s; coordinates error is less than 0.45m. It can provide a dynamic three-dimensional position, three-dimensional velocity and time information with high precision. The dynamic GPS collects the vehicles’ speed and tracks to reflect the state of the vehicle and the driver’s behavior, as shown in figure 4(a).

Vehicle-Mounted Laser Pavement Roughness Meter
Vehicle-Mounted Laser Pavement Roughness Meter uses detecting system combined with laser sensors and vertical acceleration sensors to test road vertical profile curves including short and long wavelength, as shown in figure 4(b). Under the condition of normal speed, the device can get the right and left wheel track’s IRI, position and speed, and do long distance fast automatic detection, storage, analysis and data processing for pavement. An IRI value is collected for each 100m.

Test Method
The drivers wore dynamic psychological and physiological parameter detectors and Eye trackers to detect the driver’s psychological and physiological parameter and fixation point. The test vehicle was equipped with dynamic GPS to test its real time speed changes and driving track. Vehicle-mounted laser pavement roughness meter car-following the test vehicle was used to test pavement IRI. In order to ensure the synchronism of the test instruments, the
timer on the instruments must be calibrated before each test. In order to effectively eliminate
the disturbing factors caused by non-pavement conditions, a researcher would follow the
tested vehicles and record the vehicle starting and stopping time, the mileage pile number,
overtaking or passing time and other abnormal driving behavior.

**IRI RESEARCH BASED ON DRIVING WORKLOAD DEGREE**

**Interactive Relationship between Driving Workload and IRI**

We matched the data collected by physiology and psychology recorder, eye tracker and GPS
g according to chronological order. We converted time to stake number by displacement
formula to obtain test array that corresponded to driving workload. Position data detected by
mobile pavement laser roughness meter were extracted to obtain IRI value that corresponded
to stake number in test array. We also eliminated anomalies such as car-following, overtaking,
and other factors that distracted normal driving. Finally, we got 41 effective samples for cars
and 37 for trucks. IRI distribution interval is (3.5, 5.2) m/km.

**Car**

We have organized and analyzed experimental data sets for cars and then obtained driver’s
driving workload degree given different road roughness, as shown in figure 5. We found that
K=0.06 is the car drivers driving workload degree tension threshold. IRI=4.2m/km is the
standard value of maintenance quality for cement concrete pavement, as stipulated by current
specification in China (8).

![Driving workload vs IRI](image)

**FIGURE 5 Variation of car drivers driving workload degree level**

Figure 5 shows that the higher the IRI, the rougher the pavement, and car drivers’
driving workload degree shows an upward trend accordingly. And when IRI≤4.2m/km,
drivers’ driving workload doesn’t surpass nervous threshold K=0.06. When IRI>4.2m/km,
drivers’ driving workload surpasses nervous threshold K=0.06, which explains that when IRI
reaches the maintenance standard value (4.2m/km), the car drivers’ driving workload doesn’t
necessarily reach the tense state.

**Truck**

We have organized and analyzed experimental data sets for trucks and then obtained driver’s
driving workload degree given different road roughness, as shown in figure 6. K=0.07 is the
truck drivers driving workload degree tension threshold in figure 6. IRI=4.2m/km is the
standard value of maintenance quality for cement concrete pavement as stipulated by current specification in China (8).

![Figure 6 Variation of truck drivers driving workload degree level](image)

Derived from the analysis of figure 6, the higher the IRI, the rougher the pavement, and truck drivers’ driving workload degree shows an upward trend accordingly. And when IRI ≤ 4.2m/km, drivers’ driving workload approaches to nervous threshold K=0.07, which illustrates that IRI was less than current standard value of maintenance quality 4.2m/km (namely this section needn’t maintenance), but truck drivers’ driving workload has reached the tense state. It can be seen that the current standard value of maintenance for cement concrete pavement can't meet the truck driver’s safety and comfortable driving demand.

The Relational Model between IRI and Driving Safety and Comfort

*The establishment and test of car’s model*

According to distribution in figure 5, using Statistical Product and Service Solutions (SPSS) statistical analysis software, we fit nonlinear relationship about logarithmic form between IRI and driving workload degree. Nonlinear function model is expressed as K=b₀ln(IRI) +b₁. In accordance with measured data, we calculated initial value of parameters b₀, b₁, b₀ ≈ 0.267, b₁ ≈ -0.339. Using SPSS statistical analysis software to analyze nonlinear regression model, we obtained estimated value of each iterative residual sum of squares and parameters b₀, b₁. When estimating 5 models and 4 derivatives, the minimum residual sum of square>s of two iterative reductions is less than acquiescent convergence criterion 1.E-08. The iteration stopped and we obtained optimal solution. According to the iterative result, the final regression equation is as formula (2).

\[ K = 0.255\ln(\text{IRI}) - 0.318 \]  

In the formula: K stands for driver's workload; IRI is the international roughness index, m/km; model applies to the design speed 60km/h highway.

Testing goodness of fit model (2), as shown in table 2, R²=0.834, model fits well and the significance of regression equations meets the requirements.
TABLE 2 ANOVA

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Square</th>
<th>df</th>
<th>Mean Square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>.113</td>
<td>2</td>
<td>.056</td>
</tr>
<tr>
<td>Residuals</td>
<td>.003</td>
<td>39</td>
<td>.000</td>
</tr>
<tr>
<td>Total uncorrected</td>
<td>.116</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>Total corrected</td>
<td>.018</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

Dependent variable: the driver's workload

a.R squared = 1-(sum of squares of residuals)/(sum of squares corrected) = .834

The establishment and test of truck’s model

According to distribution in figure 6, using Statistical Product and Service Solutions (SPSS) statistical analysis software, we fit nonlinear relationship about logarithmic form between IRI and driving workload degree. Nonlinear function model is expressed as $K = b_0 \ln(\text{IRI}) + b_1$. Based on measured data, we calculated initial value of parameters $b_0$, $b_1$, $b_0 \approx 0.267$ and $b_1 \approx -0.339$. Using SPSS statistical analysis software to analyze nonlinear regression model, we obtained estimated value of each iterative residual sum of squares and parameters $b_0$, $b_1$. When estimating 5 models and 4 derivatives, the minimum residual sum of squares of two iterative reductions is less than acquiescent convergence criterion $1.E-08$. The iteration stopped and we obtained optimal solution. According to the iterative result, the final regression equation is as formula (3).

$$K = 0.301 \ln(\text{IRI}) - 0.364 \quad (3)$$

In the formula: $K$ stands for driver's workload; IRI is the international roughness index, m/km; model applies to the design speed 60km/h highway.

Testing goodness of fit model (3), as shown in table 3, $R^2 = 0.767$, model fits well and the significance of regression equations meets the requirements.

Table 3 Analysis of Variance Table

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Square</th>
<th>df</th>
<th>Mean Square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>.214</td>
<td>2</td>
<td>.107</td>
</tr>
<tr>
<td>Residuals</td>
<td>.007</td>
<td>35</td>
<td>.000</td>
</tr>
<tr>
<td>Total uncorrected</td>
<td>.220</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Total corrected</td>
<td>.028</td>
<td>36</td>
<td></td>
</tr>
</tbody>
</table>

Dependent variable: the driver's workload

a.R squared = 1-(sum of squares of residuals)/(sum of squares corrected) = .767

SAFETY AND COMFORT THRESHOLD OF IRI

Pavement roughness is a significant factor which influences the driver’s driving workload. Roughness threshold selection is very important to reduce driver’s driving workload and ensure the driving safety. According to the quantitative model of driver's driving workload and IRI, we take the threshold of safety classification of driving workload at table 1 into the model (2) and model (3) to get the recommended IRI threshold values of road section with different risk level for car and truck drivers, as shown in table 4.
From the analysis of table 4, the IRI threshold satisfying driver’s safety and comfort should be kept in $\text{IRI} \leq 3.9\text{m/km}$ and $\text{IRI} \leq 3.8\text{m/km}$, for car and truck drivers respectively. The current standard value for IRI design is $2\text{m/km}$ in China, which can satisfy driver’s safety and comfort; The current standard value of maintenance quality for cement concrete pavement in China is $4.2\text{m/km}$, which is significantly higher than car and truck driver’s safety and comfort threshold.

### CONCLUSIONS

The mathematical relationship between international roughness index (IRI) and driving workload is determined by real vehicle experiment, based on the theory and measurement of driving workload, and the threshold of driving comfort and safety. For cement concrete pavement of a freeway with a design speed of 60 km/h, followings are the conclusion of the relationship:

1. (1) Pavement roughness has influence on driving comfort and safety. The higher the IRI is, the higher the driving workload will be, and the driving will become more uncomfortable and unsafe.

2. (2) When IRI comes to the standard value for pavement maintenance in China ($4.2\text{m/km}$), the driving workload of a car driver will be very close to the threshold of 0.06, and the road has relatively high risk. Meanwhile the driving workload of a truck driver will reach the threshold of 0.07, and the road has very high risk.

3. (3) For car’s model the relationship between IRI and driving workload ($K$) is

$$K = 0.255\ln(\text{IRI}) - 0.318$$

For truck’s model the relationship is

$$K = 0.301\ln(\text{IRI}) - 0.364$$

Then the IRI thresholds is obtained (table 4).

### ACKNOWLEDGMENTS

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6. Yang, W. Research on Asphalt Pavement Evaluation Method Based on

### TABLE 4 Safety and Comfort Threshold of IRI

<table>
<thead>
<tr>
<th>Security Level</th>
<th>Car</th>
<th>Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safe</td>
<td>$\text{IRI} \leq 3.9\text{m/km}$</td>
<td>$\text{IRI} \leq 3.8\text{m/km}$</td>
</tr>
<tr>
<td>Relatively Risky</td>
<td>$3.9\text{m/km} &lt; \text{IRI} \leq 4.4\text{m/km}$</td>
<td>$3.8\text{m/km} &lt; \text{IRI} \leq 4.2\text{m/km}$</td>
</tr>
<tr>
<td>Highly Risky</td>
<td>$\text{IRI} &gt; 4.4\text{m/km}$</td>
<td>$\text{IRI} &gt; 4.2\text{m/km}$</td>
</tr>
</tbody>
</table>
human-vehicle-road interaction. Xi’an, Chang’an University, 2009.


