Evaluating Alignment Consistency for Mountainous Expressway in Design Stage: A Driving Simulator-Based Approach

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ABSTRACT:
Evaluating design consistency is of great significance for safety evaluation on roadway design prior to its construction. Conventional design consistency showed little consideration of driving performance due to the limitation in data availability. More importantly, they were performed only on the existing roads. In this study, a simulated driving experiment was carried out in a high-fidelity driving simulator in Tongji University (Shanghai). A design stage four-lane (two-ways) mountainous expressway was implemented geo-based on the basis of the detailed road design blueprint. We attempted to establish a practical approach for evaluating its design consistency through investigating operating speed consistency, vehicle stability and vehicle lateral offset (vehicle trajectory). Specifically, the speed consistency is studied using the classic indicators – the 85th speed reduction and 85th maximum speed reduction. The vehicle stability was evaluated using lateral acceleration, rollover coefficient and the conventional side-friction parameter. In the lateral offset analysis, the adjusted lateral offset was newly proposed, which is defined as the lateral offset from ideal vehicle trajectory. Utilizing the adjusted lateral offset can reflect the trajectory variation dependent on the characteristics of road geometry, which leads to the discovery of the inconsistencies in the studied mountainous expressway. The lateral acceleration and rollover coefficient could be considered as supplementary measures to provide insights into drivers’ comfortableness as well as the rollover risk. Another contribution of this work is that we developed predicting models for the considered consistency measures. The purpose is to better understand the relationship between driving performance and roadway geometry characteristics, as well as to provide a practical formulation in a rigorous manner for road design consistency evaluation.

KEYWORDS: Tongji Driving Simulator; Road Safety; Design Stage; Design Consistency Evaluation; Driving Performance
1. INTRODUCTION

Since 1997, China has witnessed the increase in its expressway mileage from 4,800km to 85,000km at the end of 2011, with an average rate of 5,728 km per year (1). The latest plan released by Chinese Department of Transportation aims to reach a total mileage of 104,000 km before the end of 2015 (2). The dramatic growth of expressway length contributed to increased crashes. In 2007, the fatalities in expressway accounted for 7.39% of total fatal crashes, while the economic loss took up more than 30% of financial ruin due to crashes. Safety in expressway thus becomes a matter of great concern and has gained significant attention from both the government and the public.

Previous studies have shown that inconsistent designs in expressway were closely associated with crash risks. An inconsistent design would violate most drivers’ expectations, increase their workloads and consequently lead to potential unsafe reactions. Thus, the design consistency evaluation has been playing a critical role in identifying safety problems for the existing roadways during the past decades. Several approaches and criteria were developed to evaluate the design consistency of roadway, mainly through analyzing the measures including operating speed, vehicle stability, and driver workload and alignment indices. Due to the limitation in data collection, less attention has been paid in the conventional design consistency analysis to driving performance and vehicle operation, which are critical in evaluating the roadway system. Some recent studies improved the conventional approaches by using instrumented vehicles. Despite the enhancement in accuracy of the field test data, these studies remained to examine the inconsistency problems on the readily built roadways only. They cannot undo the lives and millions of dollars already lost before the roadway undergoes necessary revision in its constructions. Therefore, it is more desirable to conduct road safety evaluation on the roadway design prior to its practical construction.

The use of driving simulators makes it possible to evaluate the road geometry design after or even before the real construction in 3D environments from the view of the future road users through visualization of complex geometric road geometry with simulation techniques. Meanwhile, the driving performance as well as vehicle operating parameters can be recorded in real-time in the driving simulators. These data would help to improve the conventional consistency evaluation from multiple aspects. It also should be stressed that the advanced simulators offer driving conditions that are extremely lifelike. Therefore, the data can accurately reflect the driver performance and vehicle operating parameters on the designed roadway configurations.

In this work, we realized a newly designed four-lane (two-way) mountainous expressway strictly geo-based on the road design blueprint on the high-fidelity Tongji Driving Simulator, currently the most realistic driving simulator in China, to identify the potential inconsistent road configurations. The purpose is to establish a practical approach for applying driving simulator to evaluate the design consistency of an expressway ahead of its construction. The measures used to evaluate design consistency in this paper include operating speed, vehicle stability and driving performance. By applying Lamm’s (3) classical safety criteria model, the speed inconsistencies in terms of Safety Criterion I and II were examined using the 85th maximum speed reduction experienced by each driver. In contrast to
the existing literatures, the vehicle stability analysis in this paper paid more attentions to vehicle operation and driving performance in terms of lateral acceleration, lateral offset and vehicle rollover coefficient. Comparisons with the conventional side friction parameters (Safety Criterion III) were also considered. Concerning for the driving performance, a new parameter - “adjusted lateral offset”, which is defined as the lateral offset from ideal vehicle trajectory was proposed. The standard deviation of lateral offset (from its ideal vehicle trajectory) was then computed to evaluate the consistency of drivers’ path. We also developed predicting models for the used consistency measures (e.g., 85th maximum speed reduction, vehicle stability and lateral offset) to provide practical approach for consistency evaluation.

2. LITERATURE REVIEW

Design consistency refers to that geometry design of a road does not violate either the drivers’ expectation or the drivers’ ability to guide and control a vehicle in a safe manner (4). Previous studies (5) showed strong correlation between highway consistency and its accident risk. Hassan et al. (6) proposed an approach based on operating speed, vehicle stability, alignment indices and driver workload to evaluate design consistency. Driving performance was also recognized as an appropriate basis for consistency quantification and a surrogate measure of safety. We shall briefly review works on the operating speed consistency, vehicle stability and driving performance in the following subsections.

2.1 Operating speed consistency

Improper changes in vehicle operating speeds are noticeable indicator of inconsistencies in geometric design (7; 8). Lamm et al. proposed the well-known three safety criteria (TABLE 1) to evaluate the design consistency quantitatively (3; 9).

<table>
<thead>
<tr>
<th>Design Class</th>
<th>Speed Difference Safety Criterion I $\Delta V$ [Km/h]</th>
<th>Operating Speed Difference safety Criterion II $\Delta V_{85}$ [Km/h]</th>
<th>Side Friction Difference Safety Criterion III $\Delta f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOOD</td>
<td>$</td>
<td>V_{85} - V_d</td>
<td>\leq 10$</td>
</tr>
<tr>
<td>FAIR</td>
<td>$10 &lt;</td>
<td>V_{85} - V_d</td>
<td>\leq 20$</td>
</tr>
<tr>
<td>POOR</td>
<td>$</td>
<td>V_{85} - V_d</td>
<td>&gt; 20$</td>
</tr>
</tbody>
</table>

Note: $V_{85}$ denotes operating speed, $V_d$ denotes design speed.

Despite of its wide applications, improvements of the safety criteria were suggested. Firstly, the speed consistency can be evaluated using the average operating speed or the instantaneous speeds collected at specific locations (e.g., midpoint, last 200m) on approach tangent alignment. Bella and Agostini (10) pointed out that different data collection approaches should have significant effects on the speed differential calculation in the tangent-curve transition. Secondly, Hirsh et al. (11) argued that the speed differential obtained via the subtraction of $V_{85}$ at two locations would underestimate speed reduction experienced
by the individual drivers. McFadden and Eletferiadou (12) then proposed a new parameter
defined as the 85th percentile of the distribution of maximum speed reduction (85MSR) to
examine the speed consistency. The speed reduction experienced by each driver became the
difference between the maximum speed \((V_{\text{max,200}})\) on the last 200 meters of the approach
tangent and minimum speed on the curve \((V_{\text{min,c}})\). That is,

\[
85\text{MSR} = (V_{\text{max,200}} - V_{\text{min,c}})_{85}
\]  

Misaghi and Hassan (13) defined the speed reduction \(\Delta V_{85}\) as the difference between
maximum operating speed on the last 200m of the approach tangent \((V_{85\text{max,200}})\) and the
minimum operating speed on curve \((V_{85\text{min,c}})\):

\[
\Delta V_{85} = V_{85\text{max,200}} - V_{85\text{min,c}}
\]  

It should be noted that the calculation of 85MSR and \(\Delta V_{85}\) may still suffer from the
problem of low data accuracy. Because they were obtained at fixed locations, they lacked the
information on continuous speed profile. In recent years, the development of driving
simulator provided improved alternatives for roadway consistency evaluation. Bella and
Agostini (10) used the CRISS (Inter-University Research Center for Road Safety) driving
simulator and found a significant difference of 11.06km/h for the speed differential and the
85MSR. These findings lead to the development of several predicting models for 85MSR for
design consistency evaluation (14).

2.2 Vehicle stability

Vehicle stability is important for ensuring road safety. Vehicle rollover and head-on
 collisions can be attributed to excessive centripetal forces when passing horizontal curve (6).
Lamm’s safety criterion III (9) was based on vehicle stability on horizontal curves (see
TABLE 1). It was suggested to evaluate design consistency through checking whether side
friction assumed \((f_{s})\) is sufficient to meet the side friction demand \((f_{RD})\) as vehicles negotiate
a horizontal curve. Side friction assumed is related to the design speed \(V_{D}\) (km/h) as (15):

\[
f_{s} = 0.25 - (2.04 \times 10^{-3}V_{D}) + (0.63 \times 10^{-5}V_{D}^{2})
\]  

Side friction demand \(f_{RD}\) is calculated using (16):

\[
f_{RD} = \left(\frac{V_{85}^{2}}{127R}\right) - e
\]  

where R is the curve radius (m); \(V_{85}\) denotes the operating speed on alignment (km/h) and e
represents super elevation rate. However, this criterion has some inherent drawbacks. Firstly,
the vehicle was considered as a mass point and the interaction between the vehicle tyres and
the pavement was ignored. Secondly, the empirical Eq.3 was developed based on research
carried out in 1930s and 1940s in United States. Cautions should be taken when they are
applied elsewhere.

2.3 Driving Performance

Driving performance can be studied using vehicle trajectory, speed profile,
longitudinal deceleration and lateral acceleration. Using the DIVAS instrumented car, Cafiso
et al. (17; 18) examined speed profile, longitudinal and lateral acceleration and curvature of
driving path along the two-lane rural roads. Interesting results in terms of the properties of
these driving performance measures were obtained. Concerning for the vehicle trajectory, it
was important to evaluate the design consistency from the view of driving behavior (19).
However, researches on the relationship between vehicle trajectories and geometric features were relatively limited. Two studies (20; 21) reviewed the effect of highway geometric features, especially horizontal curves, on vehicle trajectory and steering angle, using a test car belonging to the University of Carleton, Canada. These studies attempted to provide recommendations to improve the horizontal curve design.

In summary, Lamm’s well-known safety criteria may suffer from lack of data accuracy. In addition, the formula to compute side friction focused on vehicle dynamics parameters only. Concerning for the driving performance, studies related to the vehicle trajectory and its relationship with design consistency is insufficient. To address these aspects, the potential benefits of using high-fidelity driving simulator to conduct design consistency evaluation have been shown in (10; 22). More researches using lateral offsets, acceleration as efficient measurements of driving performance and vehicle operations are needed.

3. METHOD

3.1 Tongji Driving Simulator

Tongji Driving Simulator is the most realistic driving simulator in China (see FIGURE 1). This simulator is an 8 degree-of-freedom (DoF) electrical motion system (6 DoF + Table XY). The active range for Table XY was 5×20 meters. An instrumented actual full car cab (Renault Megane III) was embedded into a dome. The force feed-back system acquires data from steering wheel, pedals, and gear shift lever. The 3 rear views were implemented by LCD monitors. The front view was implemented by an immersive cylindrical projection system. The field of view was 250° × 40° (5 projectors). The resolution was 1400 × 1050 for each projector with the refresh rate of 60Hz. The new generation of SCANeR™ software, SCANeR™ studio, drives the whole system, enabling realistic driving scenarios, driver immersion in a controlled virtual and highly realistic environment, and improved experimental data collection ability.

To validate the overall performance of the driving simulator, three specific tests, Simulator Sickness Test, Stop Distance Test and Traffic Sign Size Test, were initiated. For the Simulator Sickness Test, 75% of the drivers cannot be sick according to the criteria defined by Simulator Sickness Questionnaire (SSQ) by Kennedy et al. (23) during a 15 min test. For the Stop Distance Test, the situation expects the driver to stop the car on a stop line. The objective is to have 75% of drivers stopping the car by braking continuously within 2 meters of the stop line. For the Traffic Sign Size Test, the objective was to compare actual measured traffic sign and the virtual representation in the simulator displayed on the screen. It is required that 75% of the drivers rate the traffic sign size as realistic. The final result showed the above three criteria have been satisfied over the pool of 30 candidate drivers.
3.2 Participants

A total of 18 males and 4 females were recruited through Internet and posters placed around Tongji University. Each of them has a total mileage driven no less than 10,000 kilometers and an average annual driven distance at least 3,000 kilometers. One of participants experienced a high degree of discomfort after the driving test and was excluded from the analysis, hence 21 drivers remaining, whose age ranged from 23 to 59 years (mean = 36.5; SD = 10.4) and held valid driving license for 1 - 36 years (mean = 9.8; SD = 9.9). Self-reported annual mileage for the last year ranged from 3000 to 40,000km. None of the participants reported using prescribed drugs or alcohol drinking that might affect driving behavior.

3.3 Experimental Roadway Configuration

The experiment course was derived from the project of Yongji expressway whose construction will start in 2012 in western Hunan Province, China. The driving scene was
reproduced in virtual reality by recreating the exact horizontal alignment, the profile, cross-section and roadside elements from the design blueprint. The road section is about 24 km long with 2 lanes in each direction, a typical mountainous expressway containing continuous small radius curves and long down-lobes. The longitudinal grade of this alignment ranged from –6.0% to +4.0% (from east to west), and the cross-section was 10.5 m wide (lane width 3.75 m and shoulder width 1.50 m). This alignment was separate subgrade designed due to the geographical environment. Considering dissimilarities in the horizontal and vertical features, an independent test course should be implemented for each direction. 105 configurations in total were made up of 34 tangent and 71 curve configurations. The geometric parameters of each configuration are summarized in the TABLE 2.

### TABLE 2 Geometric Features of the Studied Configurations

<table>
<thead>
<tr>
<th>Geometric Characteristics</th>
<th>Variable</th>
<th>Num</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>S.D.</th>
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<tbody>
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<td>West Bound Profile</td>
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<tr>
<td>Curving Configurations</td>
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<td></td>
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<td></td>
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<td>25.48</td>
<td>131.2581</td>
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<td>0.008</td>
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<td>222</td>
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<td>447.7221</td>
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<tr>
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<td>42</td>
<td>641</td>
<td>145.5989</td>
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<tr>
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<td>80</td>
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<td>20.67963</td>
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<td>East Bound Profile</td>
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<td>Curving Configurations</td>
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<td>Bending Radius</td>
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<td>0.008</td>
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<td>0.016</td>
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<tr>
<td>Tangent Configurations</td>
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<td></td>
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<td>0.028</td>
<td>0.005</td>
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</tr>
</tbody>
</table>
3.4 Experiment Procedure

The experiment consists of two sub-courses, one on the West Bound (WB) profile and the other on East Bound (EB) profile. Both used dry pavement conditions in daylight, with the free flow traffic on two driving lanes and a low traffic distributed randomly on the opposing lanes. FIGURE 2 shows an exemplary scenario when driving in the simulator. The experiment procedures are as follows:

a) Participants are informed briefly about the experiment content such as driving task and the use of the steering wheel, pedals and automatic gear.

b) Finish questionnaires for collecting the basic information, including personal information, driving experience especially in mountainous expressways.

c) Participants enter the car and adjust the driving environment. Trainings on a specific alignment for 10 minutes are then provided so that they can get familiar with the driving simulator.

d) Drive on the alignment of the mountainous expressway in consideration for the first test course, from east to west (configuration 1 to configuration 51).

e) 5 minutes break after the first course, and fill the questionnaire about discomfort.

f) Begin the 2nd test course in the expressway from west to east (configuration 52 to configuration 105), and fill the questionnaire about discomfort for this round.

![FIGURE 2 Study mountainous expressway (a) and test Driving (b)]

3.5 Data Collection and Analysis

The data recording system collected the desired parameters at a frequency of 20Hz. They include speed, lateral offset to the central axis of road, and vertical loads on tyros. The raw data were first averaged over a distance of 5 meters along the two-way test alignment and matched with the road mileage.

Next, the consistency measures were computed. Specifically, the 85th speed reduction ($\Delta V_{85}$) and 85th maximum speed reduction (85MSR) were determined using Eq. 1 and Eq. 2. The side friction was computed via Eq. 3 and Eq. 4. A rollover coefficient was developed to indicate nearness to wheel lit-off (24) based on the distribution of wheel-terrain contact forces. From the equilibrium of vertical forces and balance of roll moments, the rollover coefficient
is defined as
\[
R = \frac{F_{Z,R} - F_{Z,L}}{F_{Z,R} + F_{Z,L}} \tag{5}
\]
where \(F_{Z,R}\) and \(F_{Z,L}\) are the tire vertical loads for the two sides. If \(F_{Z,R} = 0\) (\(F_{Z,L} = 0\)), then the right (left) wheels lift off and the rollover coefficient would take the value \(R = -1\) (\(R = 1\)). For straight driving on a horizontal road and symmetric load, \(R\) becomes zero because \(F_{Z,R} = F_{Z,L}\). The procedure to calculate the standard deviation of lateral offset (SDLO) would be introduced in section 5.3.

4. DESIGN CONSISTENCY EVALUATION

In this section, the design consistency of the simulated mountainous freeway is evaluated in terms of operating speed consistency, vehicle stability and driving performance. The operating speed consistency and vehicle stability were first analyzed following the classical Safety Criteria I-III. The lateral acceleration and rollover coefficients were included to generalize the investigation of vehicle stability. In the driving performance evaluation, drivers’ lateral offset was studied to reflect the vehicle trajectory consistency.

4.1 Operating Speed Consistency

The speed difference (Safety Criterion I) and operating speed difference (Safety Criterion II) were applied to evaluate the speed consistency using 85MSR and \(\Delta V_{85}\). The obtained results are visualized in FIGURE 3. Almost 70% configurations were identified as “POOR” according to Safety Criterion I. This implied the operating speed did not match with the design speed. As for the operating speed consistency (Safety Criterion II), the speed reduction \(\Delta V_{85}\) showed a significant underestimation over 85MSR. The paired \(t\)-test showed the difference between \(\Delta V_{85}\) and 85MSR was 7.07 km/h \((p<0.0001)\), which is close to the value of 7.55 km/h reported by Misaghi and Hassan \((19)\).

It should be noted that the maximum operating speed \((85^{th} \text{ percentile speed})\) averaged over the test alignment was 108.16 km/h, which is 13.46 km/h higher than the value \(94.7 \text{ km/h}\) suggested by Lamn and Choueiri \((25)\) and 10.26 km/h higher than that from Krammes et al. \((26)\). In other words, the observed operating speed for the test alignment was a little bit higher than the previous reported values examined by using fixed-location measures. This might be due to the fact that utilizing fixed-location data was not able to identify the real maximum operating speed. In fact, Bella and Agostini \((10)\) recently reported the average operating speed as 123 km/h for independent tangents and 114 km/h for non-independent tangents using the CRISS driving simulator, which is similar to our observations.
4.2 Vehicle Stability

Vehicle stability was examined by the following three measures: Safety Criterion III, lateral acceleration and rollover coefficient. The Safety Criterion III, 85th percentile of maximum lateral acceleration and rollover coefficient across 21 subjects were computed for each configuration. The results are plotted in FIGURE 4. Concerning the threshold equals to 0.9 (24) when a rollover collision is likely to occur, the study configurations did not show a high probability of rollover risk.
FIGURE 4 Vehicle stability evaluation for two-way test alignment – WB (a) and EB (b)

4.3 Lateral Offset

The raw lateral offset data was obtained as the absolute lateral distance to the centerline of roadway. As shown in FIGURE 5, it was observed that the raw lateral offset was “noisy” during the wave peak and trough. In order to remove these observed transient effects in the averaged data due to e.g., the difference of response time in the changes under road conditions, drivers’ minor adjustment for vehicle trajectory, we apply a first-order moving average (MA) model (with the coefficient of 0.95) to smooth the data [27]. The obtained results are included as a solid blue curve in the figure. It depicts more clearly the trend of the objects in selecting the vehicular position with respect to the road centerline along the test driving process.

It should be pointed out that the smoothed curve should be considered as an “ideal consistent trajectory” when the driver negotiates horizontal curve. The deviation of the raw data (black dotted curve) from its smoothed version (blue) would then reflect to some extent the impact of the road properties, especially, the curvature radius and superelevation rate, on the responsiveness of drivers. This means that the drivers need to do more steering adjustment in order to compensate for these observed lateral offset deviations from its ideal vehicle trajectory. The larger the adjusted lateral offset is, the further the roadway impact would be. FIGURE 5 shows that the variations in “adjusted lateral offset” well correlate with the roadway curvature.
In order to quantify the “adjusted lateral offset” along the test mountainous freeway alignment, the standard deviation (from its ideal vehicle trajectory) of lateral offset and maximum adjusted lateral offset were computed for each configuration. The standard deviation of lateral offset (SDLO) was computed as:

\[
\text{Offset}_{SD} = \sqrt{\frac{\sum_{i=1}^{N} (y_i - y_{i,\text{avg}})^2}{N}} \tag{3}
\]

where \(N\) is the total number of observed samples during the specific configuration, \(y_i\) is the \(i\)th observed lateral offset and \(y_{i,\text{avg}}\) is the moving average value for the \(i\)th sample. It should be stressed that \(\text{Offset}_{SD}\) actually measures the magnitude of deviation from vehicle’s ideal consistent trajectory within each configuration induced by the design inconsistency of roadway.

FIGURE 6 showed the evaluation results from 85% percentile of standard deviation of lateral offset and maximum adjusted lateral offset across the 21 drivers. The results showed that the standard deviation of lateral offset was averaged to be 0.385m for curves and 0.280m for the tangent alignments. This implied that when drivers negotiate on tangents, the road impact on lateral offset was significantly lower, while for the horizontal curvatures, lateral offset were more impacted by the road geometry.
4.4 Summary of design consistency evaluation

Statistical analysis showed that the consistency measures including 85MSR, 85th peak LA, 85th peak rollover coefficient and 85th SDLO data fit normal distributions at 1% significance level (Shapiro-Wilk Test coefficient = 0.929, 0.962, 0.950, and 0.934). By adopting the approach from Cafiso et al (17), the values of the 50th (median) and the 85th percentile were used as thresholds for the “FAIR” and “POOR” consistency levels. Regarding the speed consistency, alignments with 85MSR ≤ 15.38km/h were deemed as “GOOD”; those with 15.38km/h < 85MSR ≤ 22.99km/h were considered as “FAIR”; those with 85MSR ≥ 22.99km/h were marked as “POOR”. Similarly, the thresholds were computed as 1.62m/s² and 2.34m/s² for 85th peak LA; 0.138 and 0.191 for 85th rollover coefficient; 0.351m and 0.464m for 85th SDLO.

Based on the above thresholds, the consistency level (i.e., “GOOD”, “FAIR”, or “POOR”) of the study configurations were identified. FIGURE 7 shows the summary of consistency evaluation results. Concerning for the vehicle stability, the Safety Criterion III identified more than 70% configurations as “GOOD”, while approximately 50% of the configurations were identified as “GOOD” via lateral acceleration and rollover coefficient. The possible reason behind the difference in evaluation results is that the conventional Safety Criteria III only took into account of horizontal curve but ignored the effect of longitudinal slope on vehicle operations.
In addition, the cross comparison showed that among the total 105 configurations: 42.86% of them reached the same level (i.e., “GOOD”, “FAIR”, or “POOR”) via 85MSR and lateral acceleration, 45.71% via 85MSR and rollover coefficient and 40% via 85MSR and lateral offset; 64.76% configurations reached same level via lateral offset and lateral acceleration, and 59.05% via lateral offset and rollover coefficient; 78.1% configurations reached same level via lateral acceleration and rollover coefficient.

Meanwhile, statistical correlation analysis was performed to examine how the consistency measures were correlated with each other. Firstly, the correlation analysis was conducted among three stability measures (i.e., $f_R$-$f_{RD}$, lateral acceleration, and rollover coefficient) to see if they are correlated with each other. Then the correlation among 85MSR, stability measures and (SDLO) were examined. The correlation analysis was performed using both Pearson Correlation and Spearman Correlation.

The correlation result showed that the three different stability measures strongly correlated with one another. The 85th percentile of peak LA is positively correlated with 85th percentile of rollover coefficient (Pearson CC = 0.908, $p<0.0001$; Spearman CC=0.92, $p<0.0001$), and negatively correlated with $f_R$-$f_{RD}$ (Pearson CC=−0.913, $p<0.0001$; Spearman CC=−0.914, $p<0.0001$). The 85th percentile of rollover coefficient was also negatively correlated with $f_R$-$f_{RD}$ (Pearson CC=−0.829, $p<0.0001$; Spearman CC=−0.835, $p<0.0001$).

Regarding the correlation among 85MSR, stability measures and lateral offset, 85MSR was not found to correlate with the three stability measures and SD of lateral offset significantly. The SD of lateral offset was found positively correlated with 85th percentile of lateral acceleration (Pearson CC=0.67, $p<0.0001$); and positively correlated with 85th percentile of rollover coefficient as well (Pearson CC=0.60, $p<0.0001$). In addition, the SD of lateral offset was negatively correlated with $f_R$-$f_{RD}$ (Spearman CC=−0.718, $p<0.0001$).

To summarize, correlation analysis revealed strong correlation among the three stability measures; furthermore, the lateral offset was found highly correlated with vehicle stability. Thus, the lateral offset could to some extent explain the vehicle stability as well. On the basis of previous considerations, attempts for defining predicting models of 85MSR, SD...
of lateral offset and 85\textsuperscript{th} percentile of lateral acceleration were performed in the following section.

5. PREDICTING MODELS FOR CONSISTENCY MEASURES

Predicting models for consistency measures are developed to illustrate the effects of road geometry features and establish practical approach for design consistency evaluation. Multivariate linear regression with a significance level of 1\% for variable selection was used throughout this section.

5.1 85MSR Prediction Model

Considering the continuous curve-tangent configurations, the observed MSR may be negative (i.e., minimum speed on tangent may be higher than the maximum speed on curve). Thus, only the configurations of tangent-curve and curve-curve were selected in developing the model. The 85MSR was the dependent variable, and geometry characteristics as well as operating speed were included as independent variables:

\[
85\text{MSR} = -39 + 10.96L + \frac{5.132}{R_{next}} + V_{85\text{avg}}
\]  

(7)

\(L\) is the alignment length in kilometers, \(R_{next}\) is the bending radius of the next continuous curve in kilometers and \(V_{85\text{avg}}\) (km/h) is the 85\% percentile of speed across averaged over all sampled locations. The value of R-square was 0.403 and the independent variables are significant. The model multicollinearity was checked using the correlation of independent variables and variance inflation factors (VIF). The maximum correlation coefficient among the independent variables was -0.321 (\(p<0.0001\)) and maximum VIF was 1.21, which verifies the model multicollinearity. The obtained model reveals that the speed reduction is linearly proportional to the alignment length, the inverse of next curve radius and the operating speed.

5.2 Lateral Acceleration Prediction Model

Lateral acceleration was selected to represent the overall performance of vehicle stability, considering the strong correlation among the three stability measures. The established linear model for the 85\% percentile of maximum lateral acceleration was:

\[
85\text{LA} = -0.207 + 0.242R + 58.57e
\]  

(8)

where \(R\) is the bending radius in kilometers and \(e\) is the super-elevation rate. The R-square was 0.799 and the independent variables were significant. The model appears to be congruent. The correlation coefficient was not significant (\(p=0.766\)) for the bending radius and super-elevation rate, taking into account the samples of the all tangent and curve alignments. The VIF was found to be 1.0, thus justifying the model multicollinearity. The model shows that the maximum lateral acceleration increases with the bending radius and super-elevation rate.
5.3 Lateral Offset Prediction Model

The prediction model for the SD of lateral offset (SDLO) was also constructed using linear regression. Considering the difference between tangent and curve alignments, two models were developed with road geometry characteristics as independent variables:

Curve alignments:

\[ 85\text{SDLO}_C = 0.349 - 0.431L_c + 0.0017\text{CCR} \]  

(9)

Tangent alignments:

\[ 85\text{SDLA}_T = 0.336 - 0.107L \]  

(10)

where \( L_c \) is the length of circular curve in kilometers, \( \text{CCR} \) is curve change rate in gon/km and \( L \) is the length of tangent alignment.

The values of R-square were 0.475 and 0.47 for two models. The independent variables are significant and the model appears to be congruent. For curve alignments, the SDLO increases as the length of circular curve decreases and the CCR increases; for the tangent alignments, the SD of lateral offset is inversely proportional to the length of tangent decreases. The multicollinearity was also checked and the VIF was 1.02, which corroborates the choice of multivariate linear model.

6. CONCLUSION AND DISCUSSION

In this study, we utilized the Tongji high-fidelity driving simulator to simulate a exemplary four-lane mountainous freeway in design stage and developed a practical approach for evaluating its design consistency. Driving behavior and vehicle dynamics data were collected for the roadway design consistency evaluation in terms of the speed consistency, lateral offset and vehicle stability. Predicting models were also developed for modeling the relation of consistency measures to the alignment geometry.

The current study demonstrated the capability of driving simulator in evaluating design consistency for design stage roads. Specifically, the high-fidelity driving simulator can provide continuous driving performance measures such as speed-profile and lateral acceleration, in addition to the data gathered fixed locations that were commonly relied on in conventional consistency studies. Our approach is also more cost-effective than the instrumented vehicles-based methods that also are able to obtain accurate data from real-life driving.

On the basis of abundant data collected from the driving simulator, the current study considered the speed consistency, vehicle stability and lateral offset (vehicle trajectory) for evaluating road design consistency. The speed reduction \( \Delta V_{85} \) and maximum speed reduction 85MSR were examined in the speed consistency analysis and a significant difference of 7.07km/h was found, similar to the previous studies \((10; 13)\). When studying the vehicle stability, the lateral acceleration and rollover coefficient were introduced besides Lamn’s \((9)\) Safety Criteria III to reflect to some extent the drivers’ comfortableness as well as the rollover risk. The proposed measures can overcome the limitation that conventional Safety Criteria III can only consider the effect of horizontal curves while ignoring the effects.
of longitudinal slopes. Regarding to the consistency analysis for driving performance, we proposed the “adjusted lateral offset”, the lateral offset from “ideal consistent trajectory”. The standard deviations of lateral offset were computed and we demonstrated its ability to reflect the actual trajectory variation induced by the design inconsistency of roadway.

The evaluation results were compared across different consistency measures. The lateral acceleration and rollover coefficient are highly correlated in evaluating vehicle stability. Moreover, these two measures based on vehicle dynamics took into account the effects of longitudinal slope that were neglected in the conventional Safety Criteria III. Additional correlation analysis was performed to investigate the relationship among the consistency measures. The maximum speed reduction (85MSR) were found to be linearly independent of the lateral offset or vehicle stability, while the lateral offset was correlated with all the three stability measures. This indicates that the lateral offset can illustrate both the variation of vehicle trajectory and the stability performance.

Three predicting models were developed to better understand the relationship between geometry characteristics and consistency measures, as well as to provide practical tools for consistency evaluation. Following conclusions were reached from the developed predicting models:

- 85MSR is positively related to the alignment length, bending radius rate of continuous alignments, and its operating speed.
- The 85th percentile of standard deviation of lateral offset is positively related the length of circular curve and curve change rate (CCR) for curve alignments; and positively to the length of alignment for tangent alignments.
- The 85th percentile of peak lateral acceleration was positively related to the bending radius and super-elevation rate.

Several possible developments were considered for the future research. Firstly, the thresholds for this study were determined only based on the samples of specific mountainous expressway. A broader sample size from different type highways will be helpful to identify more general thresholds; Secondly, it may be valuable to consider how to combine the lateral offset and stability measures to provide more practical consistency evaluation approach.

**REFERENCE**


