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# Safety Evaluation of Combined Alignments of Freeway: a Driving Simulator Study

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**Abstract**

Combined horizontal and vertical alignments are frequently used in mountainous freeways, but there is little quantified analysis of them for application in current design regulations and standards. This study develops a method to evaluate the safety of combined alignments, using speed differential as the indicator of safety. A simulated driving experiment was carried out in a high-fidelity driving simulator. Combined alignments were classified into four types (upslope-curve, downslope-curve, crest vertical curve-curve and sag vertical curve-curve), and four Random Effects Logistic Regression models were established. Various geometric characteristics were adopted as independent variables, including the average grade, radius, curvature change rate, length of the curve and so on. The models showed that slope, curvature, length and turn direction had significant influence on vehicle stability.


*Keywords:* Combined Alignment; Driving Simulator; Speed Differential; Safety Evaluation; Freeway

## 1. Introduction

As an important component of national transportation, freeways have developed rapidly these last ten years in China, from 41,000 km (2005) to 104,400 km (2013), increasing by about 2.5 times [1]. According to the current plan for the Chinese national freeway network, by the year 2030, 118,000 km of freeway will be constructed [2]. Due to the large amount of mountainous terrain in China, many of the new freeways will be through mountainous

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areas [3]. Restricted by the terrain, combined alignments will be applied but in China, there is still a lack of thorough quantitative guidelines for combined alignments.

In order to ensure safety on combined alignments, design consistency on combined alignments should be evaluated. Design consistency represents the uniformity of the highway alignment and its associated design element dimensions [4], and its verification is particularly effective in the improvement of road safety [5]. Because design consistency verification is needed for the improvement of safety conditions, quantitative models of geometric characteristics and design consistency are necessary for the effective design of highways [5].

Consistency of alignment has been shown to steady vehicle speed and drivers' behavior in response to surprising events. Because vehicle speed can reflect design consistency, speed differential between successive elements has been an important indicator of consistency and safety [6; 7; 8; 9; 10; 11; 12].

In the current study, a mountainous freeway in Hunan Province with 64 combined horizontal and vertical alignments was modeled using Tongji University's Driving Simulator. Four combined alignment types were separately examined: upslope-curve, downslope-curve, crest vertical curve-curve, and sag vertical curve-curve. Speed differential as the indicator of safety was calculated to evaluate these combined alignments and Random Effects Logistic Regression models were used to estimate the effects of alignment. Based on the relationship between the geometric characteristics of combined alignments and speed differential, engineers can make safer modifications of combined alignments in the design stage.

## 2. Literature Review

Previous studies show strong correlation between highway design consistency and its accident risk [13]. Numerous studies have attempted to reduce the crash risk by improving speed and driving performance as related to highway geometric design [14]. Speed has been widely used in previous studies to evaluate highway consistency. A review of the relationship between driving speed and the risk of road crashes shows that speed is a crucial factor in road safety and crash risk [15; 16]. Cafiso and La Cava [14] found that the maximum driving speed differential between successive elements, the sections' average speed, and the minimum single element speed correlated statistically with accident history. Bella [17] evaluated the speed differential between tangents and curves, and developed the speed differential values model. Most research, however, has been based on the horizontal curve without considering the vertical curve; few studies have taken the vertical curve geometric features into the prediction model of vehicle speed.

Random changes in vehicle operating speeds are noticeable indicators of inconsistency in geometric design [18]. Speed consistency can be evaluated using the average operating speed or sampled speeds collected at specific locations (e.g., midpoint, last 200 m) on the approach tangent alignment. The difference between $V_{85,t}$ and $V_{85,c}$ is usually calculated as speed differential to evaluate design consistency in the tangent-curve transition [6; 7; 19]: $V_{85,t}$ is the 85 percentile of the speed 200 meters away before entering the curve (the use of 200 m is concluded from Fitzpatrick et al. [13]); and $V_{85,c}$ is the 85th percentile of the speed on the middle point of the curve. Hirsh [8], however, found this method would underestimate speed differential.

Misaghi and Hassan [10] improved the initial method (difference between $V_{85,t}$ and $V_{85,c}$ ) by proposing a new indicator, Δ85V. They chose two fixed points, usually the 100 m point before entering the curve (AT) and the middle point of the curve (MC). For each driver, difference between the speed at AT and MC was calculated. Δ85V is the 85th percentile of the speed difference between two points. McFadden et al. [20] proposed another indicator, 85MSR. 85MSR is the 85th percentile of the maximum speed reduction among all drivers in the tangent-curve transition. In this study, our research object was not the tangent-curve transition, but combined alignments, so a new calculation of the speed differential derived from 85MSR was defined as the difference between the maximum speed and the minimum speed in each of the combined alignments.

The adoption of the 85th percentile value, or average value, of all the drivers, however, may ignore the difference between individuals. Many studies have shown that a driving simulator is useful equipment for collecting highway data and examining the impact of individual driver differences, as well as vehicle technology and roadway design [21]. Driving simulators can build a virtual reality highway environment that is more efficient and safe than field research. It can reduce data deviation, and simulate not only an existing highway, but also a highway under design.

The limitations of driving simulators are also obvious. In order to provide us with a useful research tool, a driving simulator must be correctly validated. But it is difficult to realize the numerical correspondence between behavior in the driving simulator and in the real world, and validation of the simulator differs for various experiments and road types. The driving simulator therefore needs to be validated before each experiment of a different type.

## 3. Data Preparation

### *3.1. Tongji Driving Simulator*

The Tongji Driving Simulator in Fig. 1 is the most realistic driving simulator in China. This high-fidelity simulator incorporates a fully instrumented Renault Megane III vehicle cab in a dome mounted on an eight degree-of-freedom motion system with an X-Y range of 20 × 5 meters. An immersive five projector system provides a front image view of 250°×40° at 1000×1050 resolution refreshed at 60 Hz. LCD monitors provide rear views at the central and side mirror positions. For this study, SCANeRTM studio software presented the simulated roadway and controlled a force feedback system that acquired data from the steering wheel, pedals and gear shift lever. A regular privately-owned car was used as the study vehicle during the experiment.

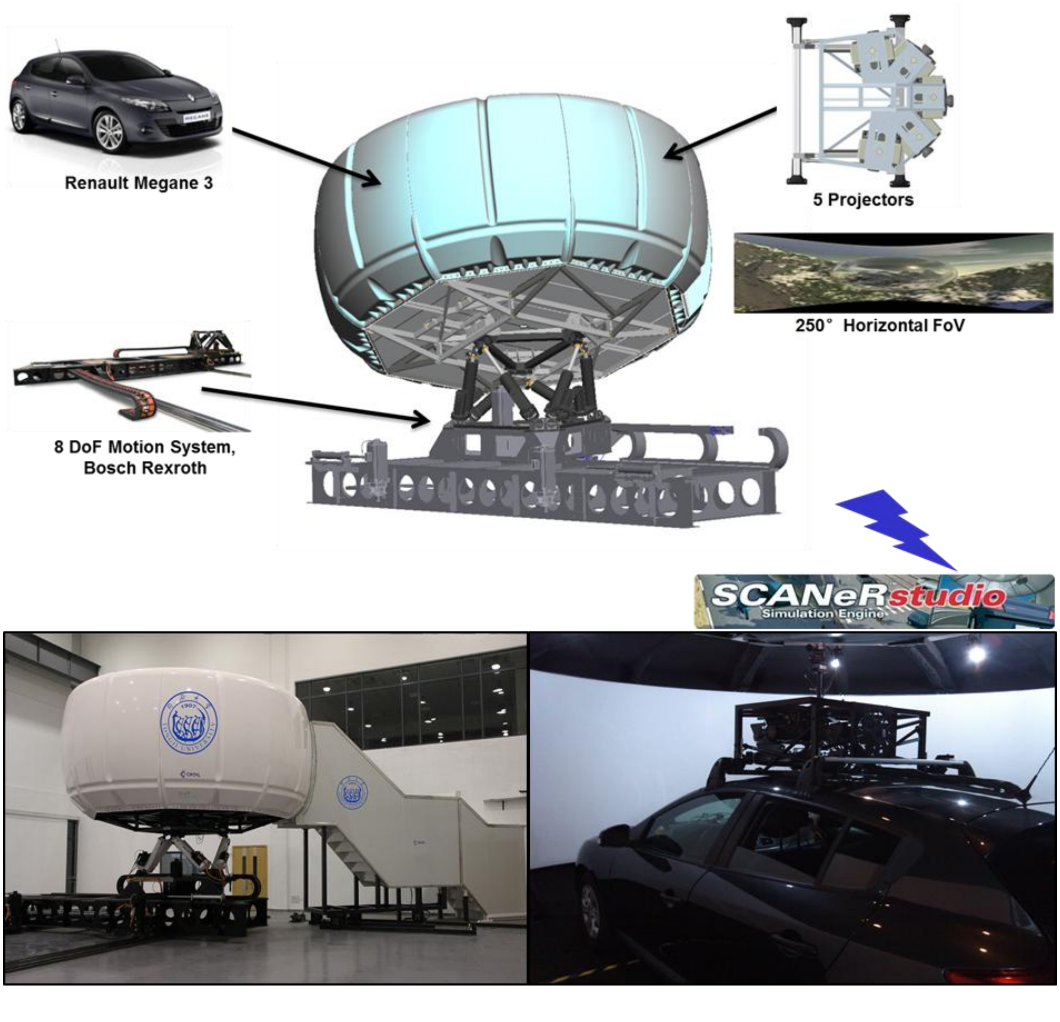


Fig. 1. Tongji driving simulator

### 3.2. Participants

Eighteen males and four females, ranging in age from 23 to 59 years, served as participants. The vision of each participant was normal. Each of them have driven a total mileage of no less than 10,000 kilometers, and an average annual distance of at least 3,000 kilometers.

One of the participants became sick while driving and was excluded from the study. None of the participants reported using prescribed drugs or drinking alcohol that might affect driving behavior.

### 3.3. Experimental Roadway Configuration

The Tongji University driving simulator was used to model the Yongji Freeway in the western Hunan province of China. Yongji is a 24 km four-lane (two-way) mountainous freeway. The longitudinal grade ranged from – 6.0% to +4.0%, and the cross-section of each direction was 10.50 m wide (lane width 3.75 m and shoulder width 1.50 m).

Sixty-four simple horizontal curve segments were selected from the Yongji Freeway. Geometric design characteristics, including grade of vertical curves, length of circular curves, curvature, circular radius, and milepost, were obtained from Computer Aided Design drawings provided by the Hunan government.

Combined horizontal and vertical alignments have distinct dependent variable profiles for design consistency indicators [22], so combined alignments were classified into four types to examine each separately:

- An upslope-curve segment is a combined segment with a vertical upslope and a horizontal curve.
- A downslope-curve segment is a combined segment with a vertical downslope and a horizontal curve.
- A crest vertical curve-curve is the curve situated on a crest vertical curve that connects a longitudinal upslope with a longitudinal downslope.
- A sag vertical curve-curve is the curve situated on a sag vertical curve that connects a longitudinal downslope with a longitudinal upslope.

Table 1 shows the geometric characteristics of the four types of combined alignments. All four types of segments involved in this study are illustrated in Figure 2.

Table 1. Geometric Characteristic of Four Types of Combined Alignments

| **Segment type** | | **Upslope-curve** | **Downslope -curve** | **Crest vertical curve-curve** | **Sag vertical curve-curve** |
|---|---|---|---|---|---|
| Number | | 22 | 22 | 10 | 10 |
| Length (m) | Mean | 398.14 | 402.45 | 367.20 | 460.90 |
| | S.D. | 136.38 | 155.72 | 143.18 | 105.00 |
| Horizontal Radius (m) | Mean | 887.91 | 847.32 | 927.60 | 572.31 |
| | S.D. | 507.69 | 391.50 | 650.83 | 142.17 |
| Average Grade of Up Slope (%) | Mean | 0.0264 | - | 0.0180 | 0.0215 |
| | S.D. | 0.0144 | - | 0.0095 | 0.0124 |
| Average Grade of Down Slope (%) | Mean | - | 0.0264 | 0.0181 | 0.0215 |
| | S.D. | - | 0.0144 | 0.0095 | 0.0127 |

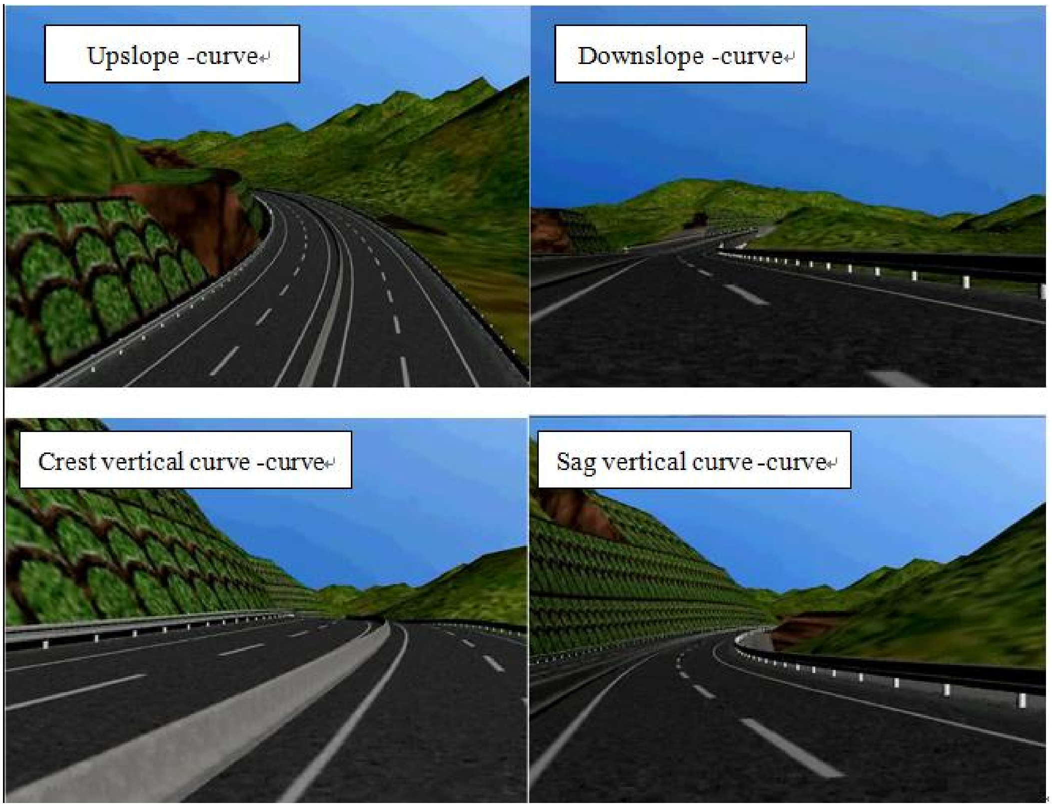


Fig. 2. Examples of combined segments on the simulated freeway

### *3.4. Experiment Procedure*

The experiment consisted of two sub-courses, one on the westbound (WB) profile and the other on the eastbound (EB) profile. Both used dry pavement conditions in daylight, with free flow traffic on two driving lanes and low traffic distributed randomly on the opposing lanes. The drivers encountered no other vehicles, as traffic effects were not of interest to this study.

The experimental sessions consisted of three phases: preparation, warm-up, and test. During preparation, participants were asked to complete a questionnaire, including their age, gender, driving experience, occupation and so on. They were informed of the nature of the simulated driving task, the potential risks, and the purpose of the study; and were then familiarized with the vehicle. They were briefed on simulator vehicle operation, and then given a 10-minute practice drive warm-up. The test followed, where all participants drove the study segments in the same order.

### *3.5. Data Collection and Measurement*

Speed data were measured and recorded at a frequency of 20 Hz. This data was then averaged over five-meter segments and related to the roadway markers.

The dependent variable was speed differential between the maximum and minimum speed on each combined alignment of each driver ($\Delta V$). Explanations of all independent variables are listed in Table 2.

Table 2. Independent Variables for Geometric Design Characteristic

| Variable | Description |
|---|---|
| $L$ | length of the whole curve (m) |
| $L_D$ | length of the negative gradient part within crest or sag segments (m) |
| $L_U$ | length of the positive gradient part within crest or sag segments (m) |
| $G$ | average grade on upslope or downslope segments (%) |
| CCR | curvature change rate ($gon \cdot km^{-1}$) |
| $R$ | radius of center circular curve (m) |
| $\Delta G$ | difference between the grades of adjacent slopes on crest or sag segments (%) |
| $G_U$ | average grade of the positive gradient part within crest or sag segments (%) |
| $G_D$ | average grade of the negative gradient part within crest or sag segments (%) |
| $L_{U-D}$ | ratio of length of the positive gradient part to length of the negative gradient part within crest or sag segment |
| Turn | curve direction, 0 for right turn and 1 for left turn |

## 4. Results

This section presents the obtained Random Effects Logistic Regression models for the four types of combined alignments. The models indicate that individual difference does influence the effects of all four combined alignments.

### *4.1. Pearson Correlation Analysis*

A preliminary analysis was carried out to identify the correlation between each pair of variables. The most common measurement of correlation is the Pearson Product Moment Correlation, whose coefficients range between -1 and +1 and measure the strength of the linear relationship between the variables. A correlation of 1 indicates that there is a perfect linear relationship between the variables. In addition to determining correlation coefficients, p-value tests the statistical significance of the estimated correlations. P-values below 0.05 indicate statistically significant non-zero correlations at the 95% confidence level. When establishing the linear regression model, one of the significant correlation variables was omitted from the model, and we will retain the variable of circle curve preferentially.

In summary, the variables G and L (below) will be included in upslope-curve segment and downslope-curve segment models. The variables $L_D$, $\Delta G$, and Turn will be included in crest vertical curve-curve segment models. The variables $L_{U-D}$, $G_U$, and R will be included in sag vertical curve-curve segment models.

### *4.2. Upslope-curve segment model*

There are 22 upslope-curve segments. The model results are presented in Table 3.

Table 3. Model Results of Upslope-Curve Segment

| Variable | Speed Differential Model | | |
|---|---|---|---|
| | Mean | confidence interval | |
| | | 2.5% | 97.5% |
| Intercept | 178 | 92.8 | 286.4 |
| G (%) | 65.2 | 34.03 | 96.43 |
| L (m) | 0.02 | 0.013 | 0.0191 |
| 1/Sigma$^2$ | 0.34 | 0.128 | 0.7402 |
| DIC | 2771.41 | | |
| $R^2$ | 0.281 | | |

The model shows that the variance of the random effects term (1/Sigma$^2$) is significant, which indicates that there are substantial differences among the drivers.

For upslope curve segments, average grade and the length of the whole curve are found to be influencing factors with a significance level of 5%. On upslope curve segments, speed differential increased by 0.652 km/h for every 0.01 increase in G, and increased by 0.02 km/h for every 1 m increase in L.

Results show that speed inconsistency is produced by longer curves and steeper grades. This can be understood as suggesting that in an upslope-curve segment, the speed differential increases as the horizontal curves become longer and the vertical grades increase.

### *4.3. Downslope-curve segment model*

There are 22 downslope-curve segments. The model results are presented in Table 4.

Table 4. Model Results of Downslope-Curve Segment

| Variable | Speed Differential Model | | |
|---|---|---|---|
| | Mean | confidence interval | |
| | | 2.5% | 97.5% |
| Intercept | 273 | 196 | 333 |
| G (%) | 97.9 | 59.8 | 136 |
| L (m) | 0.02 | 0.012 | 0.02 |
| 1/Sigma$^2$ | 0.31 | 0.111 | 0.74 |
| DIC | 2927.71 | | |
| $R^2$ | 0.263 | | |

The model shows that the variance of the random effects term (1/Sigma$^2$) is significant, which indicates that there are substantial differences among the drivers.

For downslope curve segments, average grade and the length of the whole curve are found to be influencing factors with a significance level of 5%. On downslope curve segments, speed differential increased by 0.979 km/h for every 0.01 increase in G and increased by 0.02 km/h for every 1 m increase in L.

Results show that speed inconsistency is produced by longer curves and steeper grades. This result is the same as the upslope-curve segment result, and likewise suggests that in a downslope-curve segment, the speed differential increases as the horizontal curves become longer and the vertical grades increase.

### 4.4. Crest vertical curve-curve segment model

There are 10 crest vertical-curve segments. The model results are presented in Table 5.

Table 5. Model Results of Crest Vertical Curve-Curve Segment

| Variable | Speed Differential Model | | |
|---|---|---|---|
| | Mean | confidence interval | |
| | | 2.5% | 97.5% |
| Intercept | 124 | -82.2 | 345 |
| $L_D$ (m) | 0.014 | 0.009 | 0.02 |
| ΔG (%) | 58 | 16 | 100 |
| Turn | -2.14 | -3.24 | -1.03 |
| 1/Sigma$^2$ | 1.5 | 0.17 | 2.72 |
| DIC | 1180.72 | | |
| $R^2$ | 0.286 | | |

The model shows that the variance of the random effects term (1/Sigma$^2$) is significant, which indicates that there are substantial differences among the drivers.

For crest vertical curve-curve segments, turning direction, ΔG and the length of the negative gradient part of the curve are influencing factors with a significance level of 5%. Results show that speed inconsistency is produced by longer negative gradient parts of the curve and the larger ΔG. Results also demonstrate that turning left is less affected in terms of speed differential than turning right. This may result from drivers' subjective feeling that turning left seems more dangerous than turning right, leading them to greater concentration. But this is likely dependent on which side of the road one drives, which differs from country to country. In China, drivers drive on the right side of the road

Speed differential increased by 0.58 km/h for every 0.01 increase in ΔG and increased by 0.014 km/h for every 1 m increase in $L_D$. Essentially, the ΔV increased as the negative gradient part became longer; ΔG became greater when turning right in the crest vertical curve-curve segment.

As ΔG increases, the speed differential increases. When the absolute value of the grade increases, vehicles will tend to travel faster on the downslope and slower on the upslope.

### 4.5. Sag vertical curve-curve segment model

There are 10 sag vertical curve-curve segments. The model results are presented in Table 6.

Table 6. Model Results of Sag Vertical Curve-Curve Segment

| Variable | Speed Differential Model | | |
|---|---|---|---|
| | Mean | confidence interval | |
| | | 2.5% | 97.5% |
| Intercept | 180 | 141 | 214.3 |
| $L_{U-D}$ | 1.54 | 0.51 | 2.57 |
| $G_U$ (%) | 91.8 | 15.02 | 168.7 |
| R (m) | 0.01 | 0.003 | 0.016 |
| 1/Sigma$^2$ | 133 | 0.15 | 198.5 |
| DIC | | 1359.2 | |
| $R^2$ | | 0.117 | |

The model shows that the variance of the random effects term ($1/Sigma^2$) is significant, which indicates that there are substantial differences among the drivers.

For sag vertical curve-curve segments, ratio of the length of the positive gradient part to the length of the negative gradient part, the grade of the positive gradient part, and the radius of the horizontal curve are influencing factors with a significance level of 5%. Speed differential increased by 1.54 km/h for every 1 increase in $L_{U-D}$, increased by 0.918 km/h for every 1 increase in $G_U$, and increased by 0.01 km/h for every 1 m increase in R.

Results show that speed inconsistency is produced by longer $L_{U-D}$, steeper average grade of the positive gradient part, and larger radius. Essentially, the ΔV increased as the positive gradient part occupied a larger part of the whole segment than the negative gradient part, and as the positive gradient part became sharper and the radius of the curve became larger.

## 5. Conclusion

To assist engineers in designing safer roads, this study developed a practical approach for evaluating the safety of mountainous highway combined alignments. The safety indicator in this study was the speed differential. In order to reveal how geometric characteristics influence the speed differential, we utilized the Tongji high-fidelity driving simulator to simulate a typical four-lane mountainous freeway. In order to take into account the difference between individuals and to point out the relationship between combined alignment and speed differential, the Random Effects Logistic Regression models was used. In order to consider the difference between various vertical alignments, the combined alignments were classified into four types. It was found that a single geometric characteristic influences the speed differential differently on different combined alignments.

For upslope curve segments and downslope curve segments, lower average grade and shorter length of the whole curve make the speed differential lower. For crest vertical curve-curve segments, turning left, shorter negative gradient parts of the curve and the smaller ΔG make the speed differential lower. For sag vertical curve-curve segments, shorter $L_{U-D}$, smaller average grade of the positive gradient part, and smaller radius make the speed differential lower.

The modeling results suggest that, in the design stage of freeways, the geometric parameters of different sections of combined alignments should be considered interdependently. Engineers should focus on the changes between each successive section. Various possible developments are considered for future research. First, it may be valuable to use variables other than speed differential as safety indicators in order to evaluate combined alignments and compare the differences between various indicators. Second, testing various vehicle types may produce different results.

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