Development of an Alignment Transition Index for Highway Alignment Consistency Assessment

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ABSTRACT

Alignment design consistency is an important highway geometric feature affecting traffic safety. Generally speaking, the smaller the difference of alignment features between successive road segments, the better the alignment consistency is and the better the highway safety is. On the basis of research works on safety effect of alignment features in terms of curvature change rate and grade, the integrated alignment index for each road segment has been developed which is in consists of alignment elements, including curve radius and grade. Then the alignment transition index has been defined as the difference of the integrated alignment index between successive road segments. It's easy to understand the alignment index can express the alignment feature and the alignment transition index can express the difference of the alignment feature between successive road segments. In this way, the alignment transition index supposes to have strong relation with alignment consistency.

A pilot study was implemented to develop the relation between the alignment transition index and alignment consistency. The relation between the alignment transition index and the speed difference between successive segments at tunnel entrance and exit has been studied based on the collection of large number of speed and alignment data. The statistical analysis shows the speed difference between successive segments has good correlation with alignment transition index. And then the relation between the alignment transition index and the speed difference between successive segments has been modeled. On this basis, the alignment consistency assessment criteria based on alignment transition index has been developed.

Keywords: Road Engineering, Traffic Safety, Alignment Consistency, Speed Difference, Tunnel

INTRODUCTION

Nowadays, road safety is a matter of great concern worldwide. Increased knowledge and experience have proved that alignment design consistency is an important highway geometric feature in terms of safety. Generally speaking, the smaller the difference of alignment features between successive road segments, the better the alignment consistency is and the better the highway safety is. Different approaches based on geometric relation design, operating speed differential, driving performance and human workload evaluation have been used to evaluate the design consistency of a road alignment. *(1, 2, 3, 4, 5)*

This paper develops an alignment transition index which can be used to evaluate the alignment consistency directly. on the basis of research works on safety effect of alignment features in terms of curvature change rate and grade, the integrated alignment index for each road segment has been developed which is in consists of alignment elements, including curve radius and grade. Then the alignment transition index has been defined as the difference of the integrated alignment index between successive road segments. It's easy to understand the alignment index can express the alignment feature and the alignment transition index can express the difference of the alignment feature between successive road segments. In this way, the alignment transition index supposes to have strong relation with alignment consistency.

In most research works on alignment design consistency, the speed difference between successive segments is used to assess alignment consistency and there has been an established consensus among researchers on the relation between speed difference and alignment consistency. *(6,7,8,9,10,11)* If the relation between the alignment transition index and the speed difference between successive segments has been find out, the relation between the alignment transition index and alignment consistency will be developed. On this basis, the alignment transition index can be used for alignment consistency assessment.

A pilot study was implemented to develop the relation between the alignment transition index and alignment consistency at tunnel entrance and exit zone. The relation between the alignment transition index and the speed difference between successive segments at tunnel entrance and exit has been studied based on the collection of large number of speed and alignment data. The statistical analysis shows the speed difference between successive segments has good correlation with alignment transition index. And then the regression model between the alignment transition index and the speed difference between successive segments has been developed. On this basis, the relation between the alignment transition index and alignment consistency has been developed based on the relation among alignment transition index, speed difference between successive segments and alignment consistency. The research result gives a new direct way to assess highway alignment consistency. What's more, the recommendation for design safer alignment has been provided.

DEVELOPMENT OF ALIGNMENT TRANSITION INDEX

Alignment Index

Different alignment indices have been proposed for a quantitative consistency evaluation of a roadway segment alignment. A FHWA study, based on the concept that problems with geometric inconsistencies arise when the general character of alignment changes between segments of roadway, suggested that a high rate of change in alignment indices increases geometric inconsistency. *(1)*After selecting several alignment indices as potential design consistency measures, only three indices showed statistically significant relationships to accident frequency and appeared to be promising for assessing the design consistency of roadway alignments. These three indices are:

- average radius of curvature for a roadway segment;
- average rate of vertical curvature for a roadway segment;
- ratio of an individual curve radius to the average radius for the roadway segment as a whole.

Based on the research works mentioned above, the alignment index was established considering the character of both horizontal curve and vertical curve.

The curvature, i.e. $1/R$, concerning the centrifugal force when driving at curve, is selected to form the horizontal curve variable which expresses the character of horizontal curve. The expression of the variable is shown as follows:

$$\sqrt[4]{\int_a^b \left(\frac{1}{R}-\frac{1}{R_0}\right)^2 dl \Big/ L} \qquad \text{(Eq. 1)}$$

The character of vertical curve is described with the grade revised factor g(i). Based on the research on the relation between vertical alignment and road safety, the grade revised factor was determined as follows:

$$g(i)=0.1594i^2-0.1626\,i+1.0415 \qquad \text{(Eq. 2)}$$

The alignment index used to measure the safety of alignment was expressed in terms of the combination of the horizontal curve variable and the grade revised factor mentioned above, shown as follows:

$$f=\left\{\xi+\lambda\cdot\left(\exp\left(m\cdot V\cdot\sqrt[4]{\int_a^b \left(\frac{1}{R}-\frac{1}{R_0}\right)^2 dl \Big/ L}+n\cdot V\cdot\sqrt{\frac{1}{R_0}}\right)-1\right)\right\}\times g(i) \qquad \text{(Eq. 3)}$$

Where

R_0 : the radius of the target point on the road segment;

R: the radius of the point adjacent to the target point on the road segment;

V: design speed;

L: the length of the road segment;

i: the average grade of the road segment;

a, b: the start point and the end of the road segment;

ξ、λ、m、n: model parameter. Based on the research works on the relation between alignment and safety, the values of the parameters are determined. $\xi=0.1$，$\lambda=0.28$，$m=0.67$，$n=0.25$. *(12)*

The alignment index has the character of spatial continuity. In other word, the value of alignment index of each point can change continuously along the road. What's more, it can be inferred that the larger the value of curvature and grade, the larger the value of alignment index and the worse the safety performance of the corresponding alignment. In this way, the alignment index can express the performance of alignment in terms of safety.

Alignment Transition Index

When developing alignment transition index, the transition point and a certain length of road segment adjacent to the transition point should be determined. Theoretically, the transition point can be any point along road. Generally, the points in the following situations are determined as the transition points because the problems on alignment consistency often exist in such situations.

- the situation where horizontal curvature changes;
- the situation where grade changes;

- the situation at the beginning and the end of road construction, such as tunnel and bridge.

Taking human reaction performance into account, the road segment in the length of three-second driving distance at design speed approaching and following the transition point should be consistent in order to avoid the unexpected events. Some scholars suggested that the road segment in the length of five-second driving distance at design speed approaching and following the transition point should be consistent. In this study, the road segment in the length of five-second driving distance at design speed approaching and following the transition point has been considered. And the alignment transition index was defined as the difference between the alignment index of road segment approaching and following the transition point.

ALIGNMENT CONSISTENCY ASSESSMENT METHOD

Indirect Analysis Method

There are two kinds of methods for analyzing the relation between road condition and safety. One is direct analysis method which will correlate the road condition with accident risk. But it is difficult to collect a large number of accident data needed for this analysis in China so far. The other is indirect analysis method which will correlate the road condition with some medium index. By modeling the relation between the road condition and the medium index and the relation between the medium index and safety, the interrelation between road condition and safety will be analyzed indirectly. The common medium indexes include operating speed, traffic conflict, physiological and psychological index. *(13, 14)*

As a large proportion of collisions have been attributed to improper speed adaptation, changes in vehicle operating speeds can be a noticeable indicator of inconsistencies in geometric design. There has been an established consensus among researchers on the relation between speed difference and alignment consistency. In this study, the indirect analysis method was adopted and the operating speed difference between successive segments was selected as the medium index.

Assessment Criteria

Unexpected changes in alignment elements create abrupt changes in operating speed that may lead to collision *(7, 8, 9, 10, 11)*. Lamm has proposed the safety criteria *(7, 9, 10, 11)*, that make it possible to quantify measurements. In Table 1 parameters and values for operating speed consistency criteria proposed by Lamm are reported, which is the consensus among researchers and suitable for this study.

TABLE 1 Safety Criterion for Design Consistency Evaluation

SAFETY LEVEL	OPERATING SPEED DIFFERENCE $\triangle V_{85}$
GOOD	$\triangle V_{85} \leq 10$ km/h
FAIR	10m/h < $\triangle V_{85} \leq 20$ km/h
POOR	$\triangle V_{85} > 20$km/h

If the relation between the alignment transition index and the operating speed difference between successive segments has been find out, the relation between the alignment transition index and alignment consistency will be developed. On this basis, the alignment transition index can be used for alignment consistency assessment.

PILOT STUDY

A pilot study was implemented to develop the relation between the alignment transition index and alignment consistency at tunnel entrance and exit zone. The relation between the alignment transition index and the speed difference between successive segments at tunnel entrance and exit has been studied based on the collection of large number of speed and alignment data.

Alignment Transition Index at Tunnel Entrance and Exit

When doing the research on alignment transition index at tunnel entrance and exit, the entrance and exit is the transition point, and the road segment in the length of five-second driving distance at design speed approaching and following the tunnel entrance or exit has been analyzed *(15, 16, 17)*. (see Figure 1 and Figure 2)

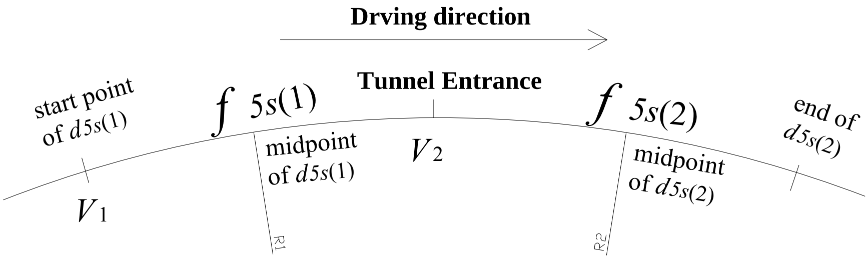

FIGURE 1 Alignment index at tunnel entrance.

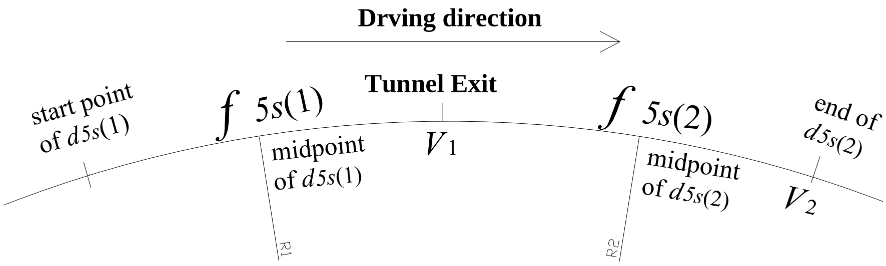

FIGURE 2 Alignment index at tunnel exit.

The road segment in the length of five-second driving distance at design speed approaching the tunnel entrance or exit was noted as $d_{5s}^{(1)}$. The road segment in the length of five-second driving distance at design speed following the tunnel entrance or exit was noted as $d_{5s}^{(2)}$. The alignment index of $d_{5s}^{(1)}$ was noted as $f_{5s}^{(1)}$, and the alignment index of $d_{5s}^{(2)}$ was noted as $f_{5s}^{(2)}$. According to the expression of the alignment index, $f_{5s}^{(1)}$ and $f_{5s}^{(2)}$ were expressed as follows:

$$f_{5s}^{(1)} = \left\{ \xi + \lambda \cdot \left(\exp\left(m \cdot V \cdot \sqrt[4]{\int_a^b \left(\frac{1}{R} - \frac{1}{R_1}\right)^2 dl \Big/ L_{5s}} + n \cdot V \cdot \sqrt{\frac{1}{R_1}} \right) - 1 \right) \right\} \times g(i_1) \qquad \text{(Eq. 4)}$$

Where

a: the start point of $d_{5s}^{(1)}$.

b: tunnel entrance or exit.

i_1: the average grade of $d_{5s}^{(1)}$.

R_1 : the radius of the midpoint of $d_{5s}^{(1)}$.

L_{5s}: the length of $d_{5s}^{(1)}$.

$$f_{5s}^{(2)} = \left\{ \xi + \lambda \cdot \left(\exp\left(m \cdot V \cdot \sqrt[4]{\int_b^c (\frac{1}{R} - \frac{1}{R_2})^2 dl \Big/ L_{5s}} + n \cdot V \cdot \sqrt{\frac{1}{R_2}} \right) - 1 \right) \right\} \times g(i_2) \quad \text{(Eq. 5)}$$

Where

b: tunnel entrance or exit.

c: the end of $d_{5s}^{(2)}$.

i_2: the average grade of $d_{5s}^{(2)}$.

R_2: the radius of the midpoint of $d_{5s}^{(2)}$.

L_{5s}: the length of $d_{5s}^{(2)}$.

The alignment transition index at tunnel entrance and exit was expressed as the difference between $f_{5s}^{(1)}$ and $f_{5s}^{(2)}$.

$$\triangle f = f_{5s}^{(2)} - f_{5s}^{(1)} \quad \text{(Eq. 6)}$$

$\triangle f$ can reflect the difference between the alignment character of $d_{5s}^{(1)}$ and $d_{5s}^{(2)}$. In other word, $\triangle f$ can reflect the transition character of alignment design at tunnel entrance and exit. As known to all, alignment consistency contributes to driving safety, so the alignment characteristics of $d_{5s}^{(1)}$ and $d_{5s}^{(2)}$ should be consistent in order to design safer driving environment. In that case, the less the absolute value of $\triangle f$, the better the alignment design.

Data Collection

In order to exclude other factors affecting driving safety at tunnel entrance and exit zone, such as signing, lighting and tunnel design characteristics, etc., tunnels with the same design characteristics have been selected in the study and all speed data were measured in sunny daytime. Operating speed is expressed by the 85th-percentile speed, selected by drivers when not restricted by other users, i.e. under free flow conditions.

Safety Assessment Criteria based on Speed Difference at Tunnel Entrance and Exit

Through the investigation on driving character at tunnel entrance and exit zone, it was found that vehicles tends to decelerate when approaching tunnel entrance, but accelerate when approaching tunnel exit*(18)*. As a result of acceleration and deceleration, the speed difference has much to do with driving safety. Generally, acceleration result in less accident, but deceleration leads to a lot accidents. According to researches on the relation between speed difference and accident rate, the accident rate is low when speed difference is less than 10 km/h, but the accident rate is high when speed difference is larger than 20 km/h. *(7, 9, 10, 11)*

Based on the above analysis, the safety assessment criteria at tunnel entrance and exit was provided as shown in Table 2 and Table 3.

TABLE 2 Safety Evaluation Criterion at Tunnel Entrance

SAFETY LEVEL	OPERATING SPEED DIFFERENCE $\triangle V_{in}$
GOOD	$\triangle V_{in} \leq 10$ km/h
FAIR	10m/h < $\triangle V_{in} \leq 20$ km/h
POOR	$\triangle V_{in} > 20$km/h

TABLE 3 Safety Evaluation Criterion at Tunnel Exit

SAFETY LEVEL	OPERATING SPEED DIFFERENCE $\triangle V_{out}$
GOOD	$\triangle V_{out} \geq 0$ km/h

POOR	$\triangle V_{out}$< 0 km/h

Note: $\triangle V_{in}=V_1—V_2$, reference to FIGURE 1. $\triangle V_{out}=V_2—V_1$, reference to FIGURE 2.

Modeling the Relationship between Alignment Transition Index and Speed Difference at Tunnel Entrance and Exit.

Theoretical analysis on the relationship

As mentioned before, $\triangle f$ can reflect the difference between the alignment character of $d_{5s}^{(1)}$ and $d_{5s}^{(2)}$. The larger the value of curvature and grade, the larger the value of alignment index and the worse the safety of the corresponding alignment.

As for tunnel entrance, when the value of $\triangle f_{in}$ is larger than zero, the alignment of $d_{5s}^{(1)}$ is better than that of $d_{5s}^{(2)}$. As the value of $\triangle f_{in}$ increase, the alignment difference between $d_{5s}^{(1)}$ and $d_{5s}^{(2)}$ increase, and the alignment consistency decrease. And hence the corresponding speed difference increase. When the value of $\triangle f_{in}$ is less than zero, the alignment of $d_{5s}^{(1)}$ is worse than that of $d_{5s}^{(1)}$. In this case, the deceleration at tunnel entrance is not serious, and the speed difference $\triangle V_{in}$ is small. What's more, in terms of the same $\triangle f_{in,}$ if V_1 is bigger, the vehicle deceleration is more serious, and the speed difference $\triangle V_{in}$ is bigger.

As for tunnel exit, when the value of $\triangle f_{out}$ is larger than zero, the alignment of $d_{5s}^{(1)}$ is better than that of $d_{5s}^{(2)}$. As the value of $\triangle f_{out}$ increase, the alignment difference between $d_{5s}^{(1)}$ and $d_{5s}^{(2)}$ increase, and the alignment consistency decrease. In this case, the acceleration is less serious, so the speed difference $\triangle V_{out}$ is less. When the value of $\triangle f_{out}$ is less than zero, the alignment of $d_{5s}^{(1)}$ is worse than that of $d_{5s}^{(2)}$. In this case, the vehicle will accelerate. If the value of $\triangle f_{out}$ is less, the difference of alignment character is bigger, so the acceleration is more serious, and the speed difference $\triangle V_{out}$ is bigger. What's more, in terms of the same $\triangle f_{out,}$ if V_1 is bigger, the vehicle acceleration is less serious, and the speed difference $\triangle V_{out}$ is smaller.

To sum up, the value of $\triangle V$ was determined by both the valure of $\triangle f$ and V_1. As for tunnel entrance, the value of $\triangle V_{in}$ increase as the value of $\triangle f_{in}$ and V_1 increase. As for tunnel exit, the value of $\triangle V_{out}$ increase as the value of $\triangle f_{out}$ and V_1 decrease.

Model Development

On the basis of theoretical analysis, the collected alignment and speed data in some tunnels was analyzed using regression method. The relationship between the alignment transition index and the speed difference at tunnel entrance and exit zone has been modeled, shown as follows:

$$\triangle V_{in}= -0.2319+0.0793\ V_1+0.8564\triangle f_{in} \qquad \text{(Eq. 7)}$$

$$\triangle V_{out}=10.3796 - 0.0604\ V_1 - 0.6564\triangle f_{out} \qquad \text{(Eq. 8)}$$

As shown in Figure 3, $\triangle V_{in}$ increase as $\triangle f_{in}$ and V_1 increase at tunnel entrance, and $\triangle V_{out}$ increase as $\triangle f_{out}$ and V_1 decrease at tunnel exit. The relation models developed using regression methods are consistent with the theoretical analysis.

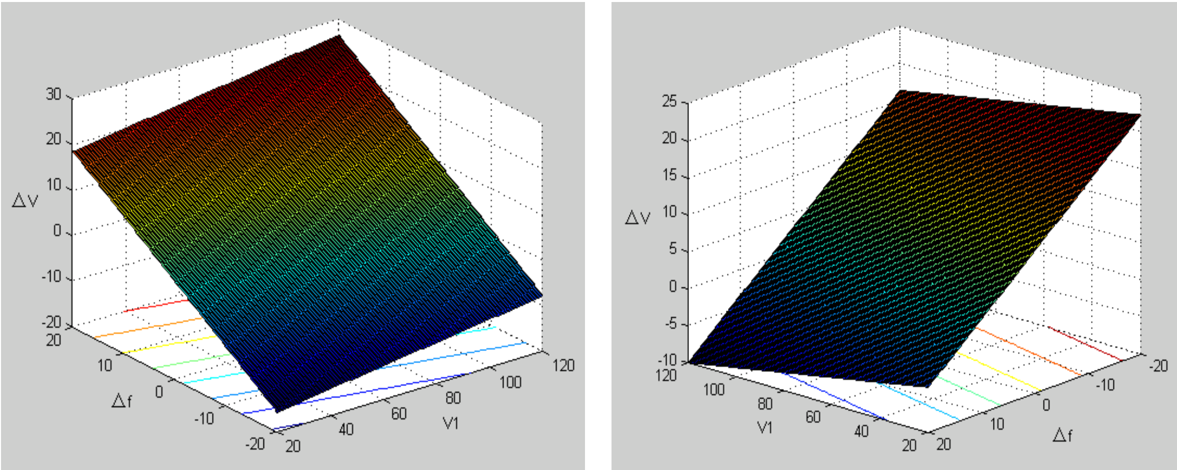

FIGURE 3 Relation model between $\triangle V_{in}$ and $\triangle f_{in}$ (left) and Relation model between $\triangle V_{out}$ and $\triangle f_{out}$ (right).

Assessment Criteria for Alignment Consistency at Tunnel Entrance and Exit

According to the models and the safety assessment criteria discussed before, the threshold values for the identification of those elements characterized by acceptable (GOOD), reasonable (FAIR) or intolerable (POOR) alignment consistencies has been recommended, shown in Table 4 and Table 5. It provides the reference for design consistency assessment and it also gives references for designing safer alignment at tunnel entrance and exit zone.

TABLE 4 Threshold Values of $\triangle f_{in}$

$\triangle f_{in}$ / V_1(Km/h)	GOOD （$\triangle V_{in} \leq 10$ km/h）	FAIR （10m/h<$\triangle V_{in} \leq 20$km/h）	POOR （$\triangle V_{in} > 20$km/h）
60	$\triangle f_{in} \leq 6.3$	$6.3 < \triangle f_{in} \leq 18.0$	$\triangle f_{in} > 18.0$
70	$\triangle f_{in} \leq 5.4$	$5.4 < \triangle f_{in} \leq 17.1$	$\triangle f_{in} > 17.1$
80	$\triangle f_{in} \leq 4.5$	$4.5 < \triangle f_{in} \leq 16.2$	$\triangle f_{in} > 16.2$
90	$\triangle f_{in} \leq 3.6$	$3.6 < \triangle f_{in} \leq 15.2$	$\triangle f_{in} > 15.2$
100	$\triangle f_{in} \leq 2.6$	$2.6 < \triangle f_{in} \leq 14.3$	$\triangle f_{in} > 14.3$
110	$\triangle f_{in} \leq 1.7$	$1.7 < \triangle f_{in} \leq 13.4$	$\triangle f_{in} > 13.4$
120	$\triangle f_{in} \leq 0.8$	$0.8 < \triangle f_{in} \leq 12.5$	$\triangle f_{in} > 12.5$

TABLE 5 Threshold Values of $\triangle f_{out}$

$\triangle f_{out}$ / V_1(Km/h)	GOOD （$\triangle V_{out} \geq 0$ km/h）	POOR （$\triangle V_{out} < 0$km/h）
60	$\triangle f_{out} \leq 10.2$	$\triangle f_{out} > 10.2$
70	$\triangle f_{out} \leq 9.3$	$\triangle f_{out} > 9.3$
80	$\triangle f_{out} \leq 8.4$	$\triangle f_{out} > 8.4$
90	$\triangle f_{out} \leq 7.5$	$\triangle f_{out} > 7.5$
100	$\triangle f_{out} \leq 6.6$	$\triangle f_{out} > 6.6$
110	$\triangle f_{out} \leq 5.6$	$\triangle f_{out} > 5.6$
120	$\triangle f_{out} \leq 4.7$	$\Delta f_{out} > 4.7$

CONCLUSION

This paper develops an alignment transition index by analyzing the transition character of driving environment along the roadway. The speed difference between successive segments has been selected as the medium index to relate the alignment transition index with the alignment consistency.

A pilot study was implemented to develop the relation between the alignment transition index and alignment consistency at tunnel entrance and exit zone. By analyzing the transition character of driving environment at tunnel entrance and exit zone, the alignment transition index and the safety assessment method have been established. The relation between the alignment transition index and the speed difference between successive segments at tunnel entrance and exit has been studied based on the collection of large number of speed and alignment data. The statistical analysis shows the speed difference between successive segments has good correlation with alignment transition index. And the regression model between the alignment transition index and the speed difference between successive segments has been developed. On this basis, the threshold values for the identification of those elements characterized by acceptable (GOOD), reasonable (FAIR) or intolerable (POOR) alignment consistencies has been recommended.

Due to the limitation of the quantity and quality of the collected alignment and speed data and the complicated factors affecting the driving character at tunnel entrance and exit, the relationship model between the alignment transition index and the speed difference discussed in this paper need be revised in the future as the data collection getting more advantageous, but this method provides a new way to do design consistency analysis which is more valuable than the model itself.

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