Space Properties of the Road Alignment and Impact on the Traffic Accident

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Abstract
Based on numerous research works on road traffic safety, the space curvature index of expressway alignments was developed considering road alignment space geometric properties and its impact on traffic accident. This index was modified to reflect the influence of the curvature on highway operating speed. The road safety performance and operating speed of several expressways were investigated and the regression relationship between single-vehicle accident rate and space curvature index of highway alignments was studied. So that the space curvature index of highway alignments could be used as a prediction factor of traffic accident in highway alignments during highway alignment safety design and road safety analysis.

Keywords: Highway safety; Road alignment; Single-vehicle accident analysis; Space curvature

INTRODUCTION

The issue of road traffic safety has been getting more and more consideration. Out of these road safety research topics, the effects of road alignment on safety are being studied at home and abroad. A number of various models and quantitative assessment methods of the road alignment (Fambro et al. 2000) have been developed. Alignment consistency in terms of vehicle speed change was used by Leisch (1977) as a representative feature of highway alignment continuity. According to the “Highway Safety Design and Operations Guide” (Ministry of Communications of P. R. China 2004) highway design consistency is defined as “the avoidance of abrupt changes in geometric features for contiguous highway elements and the use of design elements in combinations that meet driver expectations". In developing them to the road safety audit guide, researchers studied the features of highway alignments and operating speed related highway traffic safety.

Quite a few research works have been conducted on predicting operating speeds. Many studies took horizontal curves and vertical sections as factors (Bella 2005; Abdul-Mawjoud and Sofia 2008), and these kinds of models established the linear consistency evaluation based on the difference of operating speed. (IHSDM 2010)

In this paper, we describe research relating with highway alignments and safety performance using an index of space geometric properties. Highway alignments can play the function guiding driver's operating and restricting traffic movement. The highway alignment (also the vehicle movement trajectory) is assumed to be a three dimensional curve. The space curvature of the three dimensional curve was adopted as the main alignment index combining the restrictions of highway alignments. Then the relationship between the index and single-vehicle crash rate was developed by investigating the road safety performance and operating speed.

METHOD

Curvature is an expression index of the curve degree of curve line generally, expressed as K. Usually the curvature of a curve can be calculated with the general curve equations as shown by equation (1):

$$\kappa(t) = \frac{\left|r'(t) \times r''(t)\right|}{\left|r'(t)\right|^3} \tag{1}$$

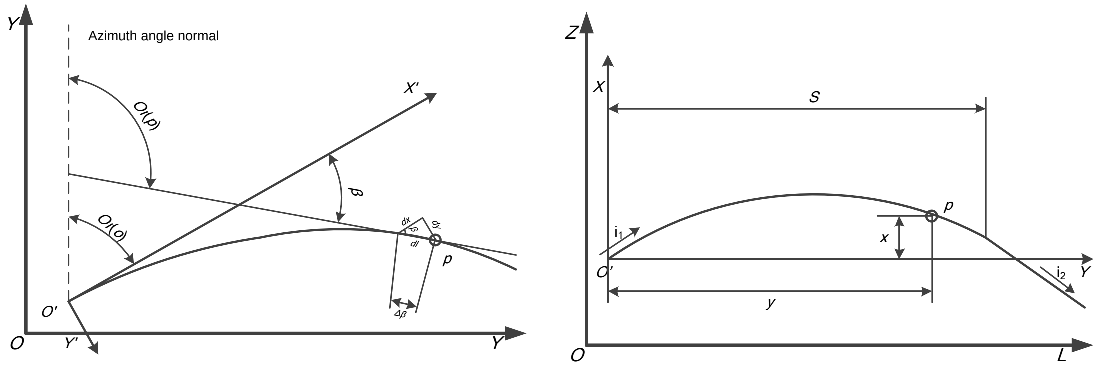
Throughout the highway alignment design, the horizontal alignment features are the priority ones to be determined. Any complex route is composed of straight segment, circular curve segment and the transition curve segment which are combined with various forms. In measuring a highway alignment in a plane coordinate system, plane coordinates (x,y) can be expressed in a parametric equation (2):

$$r(x, y) = (F_x(l), F_y(l)) \tag{2}$$

Where, l is the station (mileage), m. This parameter equation is a piecewise function. $F_x(l)$ and $F_y(l)$ have different expressions respectively for straight segment, circular curve segments and transition curve segments.

Any curve element can by expressed by the curvature radius at the start point of and the end point of the curve, R_o, R_e and the length of the curve, s. The coordinate (x,y) any point of a horizontal curve can be determined with the station of the horizontal start point. Let the distance of the calculation point p is l=L_p-L_o, curvature is κ, declination angle is β, the distance of the curve segments S=l_e-l_o.

A clothoid is applied in the design of an expressway's horizontal curve, which connecting a circular curve and a straight line, whose alignment is spiral. The radius of the convolute curve changes from radius R_o to R_e. When designing the convolute curve, the general formula for calculating coordinates taking the coordinates of any point as the origin coordinate, the calculation may be greatly simplified.[Tang and Wu 2006] The curvature of the convolute curve changes with distance linearly. The curvature at any point of the convolute curve $k_i=1/R_i=k_o+l(k_e-k_o)/S$. After the temporary coordinate system $X'O'Y'$ is established as shown in Figure 1(a), the convolute curve can computed.



(a)Horizontal Curve **(b)Vertical Curve**

Fig.1 Coordinate Calculation of Road Alignment

Taking the differential distance $dl=R_i d\beta \Rightarrow d\beta=k_i dl$, equation (3) can be deduced.

$$\beta = \int_0^l k_i dl = k_o l + \frac{k_e - k_o}{2S} l^2 \tag{3}$$

According to the computing formula of the temporary coordinate system, let the curve length at the calculated point p, equal to l, the point coordinates in the temporary coordinate system are:

$$\begin{cases} x = \int_0^l \cos\beta dl \\ y = \int_0^l \sin\beta dl \end{cases}, \text{ which, } \beta = \int_0^l k_i dl = k_o l + \frac{k_e - k_o}{2S} l^2 \tag{4}$$

Taking straight lines and circular curves be special forms of the convolute curve, the formulas also can be used to compute straight line segments and circular curve segments.

The vertical alignment plays a longitudinal transition, ensuring a smooth ride and adequate sight distance. The parabola or circular curve with large radius is used generally as a vertical curve. The vertical curve length at the calculated point p is $l=l_i-l_o$, the altitude at starting point is z_o, slope difference $\omega=i_1-i_2$ and the curve segment length $S=l_e-l_o$. Where the quadratic parabola is used for vertical curve, straight line segments connect to the parabola at each ends and the entire slope is constituted. After the temporary coordinate system $XO'Y$ is established as shown in Figure 1(b), the quadratic parabola as a vertical curve can be computed.

The function for quadratic parabola curve within the temporary coordinate system can be expressed by equation(5).

$$x = ay^2 + by, i = \frac{dx}{dy} = 2ay + b \tag{5}$$

The quadratic parabolic formula of vertical curve can obtained putting the coordinates value at the end of the vertical curve, as shown in equation(6):

$$z = z_o + \frac{\omega}{2S} l^2 + i_1 l \tag{6}$$

As talking about horizontal curve above, the calculation formula of vertical curve segment can be applied to computing straight line segments.

The projected curve length t (mileage, l) at *XOY* plane is as the only parameter while develop the three-dimensional mathematical model of expressway alignment in this paper. Combining the results previous derived, the space curve of expressway alignment can be expressed as:

$$r(t)=(\int_0^t \cos(k_o t+\frac{k_e-k_o}{2S}t^2)dt, \int_0^t \sin(k_o t+\frac{k_e-k_o}{2S}t^2)dt, z_0+\frac{i_e-i_o}{2S}t^2+i_o t) \quad (7)$$

The start and end point of the alignment segment are defined in accordance with horizontal and vertical alignment respectively. By putting expressway alignment equation into formula (1) and making simplification, the space curvature of expressway alignment can be computed using the following expression (8):

$$\kappa(t)=\frac{\sqrt{(\frac{i_e-i_o}{S})^2+(\frac{i_e-i_o}{S}t+i_o)^2(k_o+\frac{k_e-k_o}{S}t)^2+(k_o+\frac{k_e-k_o}{S}t)^2}}{(1+(\frac{i_e-i_o}{S}t+i_o)^2)^{3/2}} \quad (8)$$

Where, $(i_e-i_o)/S*t+i_o$ is the linear interpolation of the vertical curve slope inside the computed alignment segment. Because the quadratic parabola is used for vertical curves, the values were equal to the slope, i_t; $k_o+(k_e-k_o)/S$, is the linear interpolation of horizontal curve curvature k of the computed alignment segment. The values is equal to the curvature k_t of the point; $(i_e-i_o)/S$ is the linear change rate of vertical curve slope i of the computed alignment segment, so let it be di_t. It has to be recognized that even though i in the z direction has great influence on operating speed, its magnitude is small compared with the influence of horizontal curve curvature. Vertical curve curvature and horizontal curve curvature have different influences with different way. The influence of curvature is produced through the action of alignment on vehicle operation. The impact of vertical slope is generated by the gravity in Z direction.

Therefore, i_t may be modified a correction factor B where computing three-dimensional curvature. The parameters B used to reflect that the action in the z direction is different from that in other two directions. So the original formula is modified to be equation (9):

$$\kappa(B)=\frac{\sqrt{di_t^{\,2}-Bi_t\left|i_t\right|k_t^{\,2}+k_t^{\,2}}}{(1-Bi_t\left|i_t\right|)^{3/2}} \quad (9)$$

DATA COLLECTION

The researchers collected crash data and measure operating speed about 200 sections of three expressways in the north east parts of China. The investigated data of expressways are shown in Table 1. The traffic-related crash data were collected from department of the police office, which includes the year of vehicle data collecting and two years before. The crash data was treated according to the types of crashes. The three-year accident data are shown in Table 2.

Table 1 Investigated Expressways

Expressways	Lane (Two-way)	Total Long (km)	Design Speed (km/h)
I	8	348	120
II	4	222	100

III	6	361	120

Table 2 Investigated Expressways and Accident Data

Expressways	Accident data					
	Accident type	Single-vehicle accident	Rear-end collision	Collision	Other	Total
Expressway I	Accident No	669	182	10	34	895
	Percent (%)	74.7	20.3	1.1	3.9	100
Expressway II	Accident No	1810	612	61	120	2603
	Percent (%)	69.5	23.5	2.3	4.7	100
Expressway III	Accident No	1142	45	1095	244	2526
	Percent (%)	45.2	1.8	43.3	9.7	100

It can be observed from the statistics of these 3 expressways that single-vehicle crash takes a large proportion in China, which is 45-75%. Vehicle information was collected by setting up the roadside detection units in the daytime during 9:00 and 17:00 under clear weather condition. The data of vehicle speeds and axles on the sections of more than 200 straight, transition and horizontal lines were collected. All the vehicles under 6s gap to the front vehicle were removed, to ensure free flow conditions. There are at least 400 vehicle records measured in each section. These records were sorted and the 85^{th} speed was selected as the representative speed.

Correction parameters were obtained by analyzing expressway operating speed. The operating speeds were derived from sample exceeding 400 vehicles per section for a total of about 200 sections along several expressways.

RESULT

Through analyzing the effects of highway alignment features on road safety and operating speed, the space curvature index was modified regarding the influence of the curvature on highway operating speed. The regression relationship between single-vehicle accident rate and the index of highway alignments was developed. Through non-linear regression analysis and considering the expressway alignment features, the calculated value of B for A-Type vehicle is 134.041 with R^2=0.730 and 250.772 for D-Type vehicle with R^2 = 0.665. The space curvature index of expressways is computed using the following equations:

$$\kappa_a = \kappa(134) \quad ; \quad \kappa_d = \kappa(250) \tag{10}$$

The section of 10 meters expressway alignment can be taken as a calculation step while the space curvature index is computed for an expressway segment for the passage car and heavy truck separately. According to research results [Miaou and Lum 1993] and preliminary analysis of some expressway sections, the following typical feature parameters are selected to be studied: the standard deviation of the space curvature of the computed segment, σ_κ; the mean value of space curvature of the computed segment, $avg\kappa$; the coefficient of variation space curvature of the computed segment, C_κ; the difference between the space curvature for passenger car and that for heavy truck, Δm_κ and the relative difference ratio, M_κ. The detail definitions of these parameters are described below:

$$\sigma_\kappa = \sqrt{\frac{OP \times \sum_{1 \le i \le n} (\kappa_{ai} - avg\kappa_a)^2 + (1-OP) \times \sum_{1 \le i \le n} (\kappa_{di} - avg\kappa_d)^2}{n-1}} \quad (11)$$

$$C_\kappa = \frac{\sigma_\kappa}{avg\kappa} \quad (12)$$

$$avg\kappa = (OP \times \sum_{1 \le i \le n} \kappa_{ai} + (1-OP) \times \sum_{1 \le i \le n} \kappa_{di}) / n \quad (13)$$

Taking into account that the difference between the space curvature for passenger car and that for heavy truck is not well indicated the discrete of the difference Δm within the computed segment, the relative difference ratio, M_κ is introduced as a parameter to reduce the impact of limited sample data:

$$M_\kappa = (\max \Delta m - \min \Delta m) / avg\Delta m \quad (14)$$

Where in Formula 11-14: κ_a is the space curvature for passenger car, m^{-1}; κ_d is the space curvature for passenger car, m^{-1}; *OP* (occupancy of passenger cars); $avg\Delta m$ is the average value of difference between the space curvature for passenger car and that for heavy truck Δm, m^{-1}.

The single-vehicle accident rate (accidents per million vehicle kilometers) of 20 expressway segments (more than more than 3,000 cross sections, *OP* is about 0.691) and the relative alignment features indicated by σ_κ, avgκ, C_κ and M_κ were investigated. The collected and analyzed results are shown in Table 3 and Table 4.

DISCUSSION

The correlation analysis results in Table 3 indicate that there is a good correlation between accident rate and typical parameters of space curvature of expressway alignments. The regression correlations between accident rate and σ_κ and M_κ are very good with level of 0.05.

Regression analysis between single-vehicle accident rate and σ_κ, avgκ, C_κ and M_κ were carried out with quadratic polynomial regression models. The regression results are shown in Figure 2. In these figures, the abscissa is the space curvature index and the vertical axis is the single-vehicle accident rate (accidents per million vehicle kilometers):

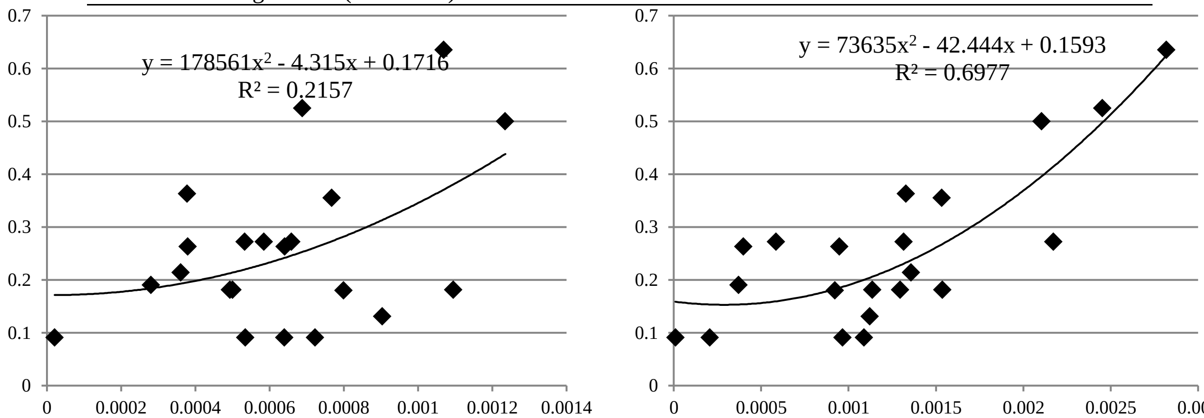
Table.3 Single-vehicle Accident Ratio and Indexes of Space Curvature in Different Road Section

Section Number	Accident Rate	Standard Deviation	Mean Value	Coefficient of Variation	Range	Range Ratio
1	0.091	0.000965	0.000722	0.749	0.000422	2.19
2	0.181	0.001135	0.000493	0.435	0.000422	3.13
3	0.181	0.001537	0.001095	0.712	0.000596	2.68
...	...	...	...	...	...	...
20	0.263	0.000947	0.000379	0.400	0.000085	2.10
21	0.214	0.001357	0.000360	0.265	0.000079	2.05

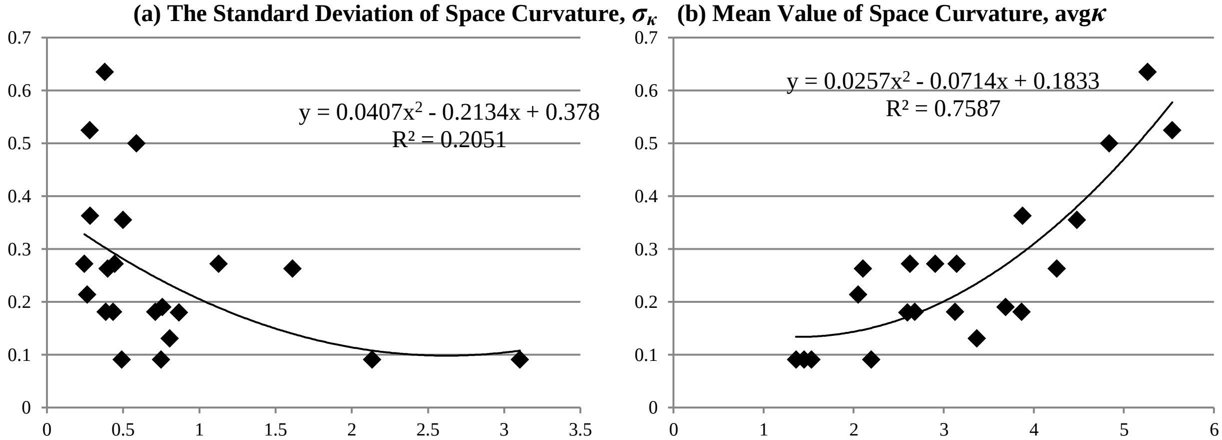
Table.4 Correlation Test of Single-vehicle Accident Ratio and Indexes of Space Curvature

		Accident Rate	Standard Deviation	Mean value	Coefficient of Variation	Range	Range Ratio
Accident	Pearson Correlation	1	.773**	.445*	-.424	.837**	.831**

Rate	Significant (both sides)	.000	.043	.056	.000	.000



(a) The Standard Deviation of Space Curvature, σ_κ (b) Mean Value of Space Curvature, avgκ



(c) Coefficient of Variation Space Curvature, C_κ (d) Relative Difference Ratio, M_κ

Fig.2 Regression Result of Single-vehicle Accident Ratio and the Alignment Indexes

The quadratic polynomial regression analysis results in Figures 4 show that: (1) there is a low correlation coefficient between single-vehicle accident rate and the standard deviation of the space curvature, and the correlation coefficient between the accident rate and the mean of the space curvature correlation is high up to 0.7. (2) the coefficient of relationship between the accident rate and the coefficient of variation space curvature C_κ is very low, only about 0.2. So the relationship between the accident rate and the coefficient of variation space curvature C_κ is not significant.

Compared with the traditional analysis method of single index and independently multiple indexes, this paper was focused on the single-vehicle accident, which is based on the highway geometric characteristics. The space curvature of the geometric design was established as the base of the safety evaluation index, and this series of evaluation indexes have good regression result (0.75).

CONCLUSION

The road safety issue is now getting more and more attention in China. The research work about the impact of highway alignment on road safety has been carried out for many years. In this paper, space features of highway alignment for the evaluation of road safety were developed and focused on the single-vehicle accident.

Unlike relatively independent alignment feature parameters which were used to indicate the road safety performance of highway alignment, the relative integrated alignment feature parameters based on the space curvature of highway alignment were studied. This could be used to evaluate the road safety performance of expressway and optimize the linear design of expressway.

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