IMPROVEMENT OF HIGHWAY DESIGN CONSISTENCY EVALUATION PROCEDURE

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Abstract: Highway design consistency evaluation procedures have been used to compliment design speed concept but still seem to show weakness, in particular in the capability of predicting vehicle speeds. In this research an emphasis was made on refining the speed prediction models using a stepwise approach. Speed prediction models made in this research are basically the results from regression analysis between speeds and local characteristics of roads including curve radii, tangent lengths, and grades of vertical alignments. Both vehicle speeds and traffic accident data were measured and collected in the field sites in southern part of Korean peninsula. Research results seem reasonable from traffic accident rate standpoint and it is recommended that highway consistency evaluation measure be replaced by the K value, a combined measure of safe speeds and running speeds for each section of highway. Software was developed to save manual computational efforts and it is expected that the improvements made in this research for highway design consistency evaluation procedure would result in more accurate and reliable predictions of vehicle speeds and accidents.

1. INTRODUCTION

Highway Design speed concept was established in 1930s and became one of the most important design standards in highway alignment design. In spite of the multiple definitions by different literatures, the idea of design speed focuses on the highest constant speed that can be maintained on the overall highway section with no limitations imposed by traffic volume, and design speed determines the minimal characteristics of the alignment. The problems related to design speed concept are that actual vehicle speeds are frequently higher than the design speed and that design speed does not prevent using a sharp curve after a straight section. To resolve the problems, design consistency check procedures have been developed and used for a while. J. Leisch's speed profile model, which evaluates highway alignment based on speed changes for successive highway sections and the 10 mph rule, is one of the forerunners (1). Others represented by Lamm's model categorize the consistency of successive alignment elements based on conventional design rules such as the German standards (2). However, these models include speed prediction models that seem inaccurate. The inaccuracy seems to be caused by ignoring that actual speeds at any point are largely determined by the local characteristics of the road.

In this research project, both speed prediction models and accident relationships for various geometric conditions in two-lane rural roads were developed, utilizing the regression analysis, for the use of checking design consistency of highway sections. Also, computer software for evaluating design consistency was made to facilitate the computational procedures.

1.1 Objectives

Prior studies of highway design consistency mostly utilized speed differences for successive highway sections as the primary measure of consistency evaluation. It was hypothesized that if design consistency was confirmed safety of the corresponding highway sections could be insured. However, it was not necessarily the case in South Korea, as traffic accident records for those sections with fair design consistency really were found to involve relatively high numbers of traffic accidents. Probably existing design consistency models failed to establish correct degrees of accuracy from the traffic accident data standpoint.

In fact, drivers will operate within speeds determined by their vehicle maneuvering capabilities. .This speed is defined as running speed throughout this research project and considered influenced remotely by other factors including road geometry, vehicle characteristics, traffic conditions, and traffic control patterns. Usually the differences of running speeds for successive highway sections tend to be relatively small, which probably is the reason why highway sections proved fair in terms of speed difference often yield inconsistent geometric conditions. Particularly, if for some reasons geometric condition of a highway section is not fully reflected in the running speed calculation procedure, the results of design consistency check become invalid. In this regard the objective of this research project is to improve existing design consistency checking models by changing the primary measure of design consistency evaluation. Notably speed prediction models for running speeds and safe speeds were improved reflecting characteristics of two-lane rural roads collected in the field sites. Also running speed prediction models for long tangent highway sections were made.

2. DATA COLLECTION

Traffic accident records used in this research project are for four year periods from 1996 to 1999 and relevant data including traffic characteristics, road geometry, and environmental conditions were surveyed July 1999, February 2000, and May 2000. The field survey sites are located in National Road 1, 27, 29, and 30, which penetrate Jeolla Buk Do in South Korea and shown in Figure 1.

Total numbers of horizontal curves and straight tangent sections within the field survey sites are 30 and 20, respectively. Curve radii are covering 50- 500 meter and all tangent sections have greater than 100 meters lengths. In this research the horizontal curves are divided by three different sections; entering section, middle section, and exit section. Two detectors are to be installed at each section. Figure 2 shows the installation of detectors at a horizontal curve.

3. SPEED PREDICTION ON A HORIZONTAL CURVE

In this research project, three types of speed prediction models are made which include safe speed, basic speed, and running speed on horizontal curves. These speeds are obtained by determining average speeds within horizontal curve sections where driver's minimum sight distance can be provided. Figure 3 shows a sample diagram showing the pattern of minimum sight distance and safe speed within a horizontal curve. Followings are the descriptions of how three different types of speed prediction models are developed in this research project.

3.1 Safe Speed and Basic Speed

The safe speed prediction model developed in this study is based on the main concept originally developed by the author (1999, 2000) on horizontal alignment. A simple description is given in the followings.

Basically three procedures are required for obtaining the safe speed on a horizontal curve. Firstly, available sight line, shown in Figure 3, is determined using horizontal curve data that include radius of curve, lane width, and lateral clearance.

$$S_L = 2\sqrt{(R - L_W/2)^2 - [R - (L_W + L_C)]^2} \tag{1}$$

where, S_L = available sight line on a curve (m)
R = radius of a curve (m)
L_w= lane width (m)
L_c = lateral clearance (m)

Also, the available sight line (S_L) in equation (1) can be expressed as:

$$S_L = 2(R - L_W/2)\sin\frac{\theta}{2} \tag{2}$$

Hence,

$$\theta = 2\sin^{-1}\left[\frac{S_L}{2(R - L_W/2)}\right] \tag{3}$$

Accordingly, the available sight distance on a curve (SD_h) is as follows:

$$SD_h = \frac{(R - L_W/2)\pi\theta}{180} \tag{4}$$

On the other hand, the minimum stopping sight distance on a horizontal curve is determined by a familiar form shown in Equation (5).

$$MSSD_h = tV_h + \frac{V_h^2}{2g(f \pm G)} \tag{5}$$

where, V_h = running speed on a curve (m/s)
t = reaction time (2.5s)
g = the acceleration of gravity (9.8m/s^2)
f = friction factor
G = vertical grade (%)

As drivers will operate with speeds that mostly is dependent upon their ability of seeing forward, it can be said that the minimum stopping sight distance obtained in Equation (5) may be used as the distance limit for finding the driver's safe speed in Equation (4). Then the safe speed on a horizontal curve is finally calculated by Equation (6).

$$V_S = -g(f \pm G)\,t + \sqrt{[g(f \pm G)\,t]^2 + 2g(f \pm G)\,SD_h} \tag{6}$$

Basic speed is determined by applying 1.0 second as drivers' perception reaction time and available friction factors to Equation (6). We name it basic speed as it is a basic speed considering ample amount of driver's comfort and freedom of vehicle maneuvers.

3.2 Running Speed

Safe speed described above forms the base of running speed model. But, after safe speed is obtained, running speed is determined by reflecting the effects of road environmental factors into vehicle speeds. For this, a thorough investigation is made in this research to develop various relationships between road environmental factors and actual vehicle speeds which were collected at the field sites. The relationships were developed using multiple regression analysis and non-linearity for each independent variable was investigated in detail. In the regression analysis, vehicle speeds were used as dependent variables and other environmental factors such as speed limit sign, access points, and lengths of long tangent sections were used as independent variables. The strength of running speed model developed in this research relates to the fact that a stepwise approach, which firstly considered safe speed and subsequently running speed, was employed.

Statistical significance, explained by t-statistic, F-ratio and R^2 obtained from the SAS(Statistical Analysis Software), for each independent variable was checked to select the best speed prediction model. It is to be noted that the observed speeds are 85^{th} - percentile speeds in cumulative speed distributions. Equation (7) illustrates the form of running speed model.

$$V_R = V_B \cdot (\alpha_0 + \alpha_1 \cdot X_1 + \alpha_2 \cdot X_2 + \alpha_3 \cdot X_3^3) \tag{7}$$

where,
V_R = estimated running speed (km/h)
V_B = basic speed (km/h)
X_1 = lengths of exiting tangent sections (km)
X_2 = number of stop signs
X_3 = number of access roads and crosswalks
α_0, α_1, α_2, α_3 = intercept and coefficients of independent variables

Table 1 shows the results of regression analyses. In table 1, α_0 is 1.0248 and implies that when other variables have zeros the running speed is equal to basic speed. Also, the values of α_1, α_2, α_3 are 0.067, -0.092 and -0.003, respectively. This means that variable X1 increases the running speed while variables X2 and X3 decrease the running speed. Table 2 summarizes the characteristics for 30 horizontal curves surveyed in this research. Table 3 and Figure 4 show the comparison results made between observed speeds and model speeds.

4. SPEED PREDICTION ON PRECEDING TANGENT SECTIONS

The previous sections explain how one can obtain vehicle speeds on horizontal curves. However, if running speeds for preceding long tangent sections for horizontal curves are to be made, engineers should be provided with additional speed estimating procedures. Basically the same type of research approach (multiple regression analysis) as used for horizontal curves was used here. Equation (8) is the model used in this research and Table 4 shows the regression results.

$$V_R^T = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \beta_3 \cdot X_2^2 + \beta_4 \cdot X_2^3 \tag{8}$$

where,

V_R^T = estimated running speed on tangent section (km/h)
X_1 = length of a tangent section (km)
X_2 = number of stop signs, access roads and crosswalks
β_0, β_1, β_2, β_3, β_4 = intercept and coefficients of independent variables

Total number of long tangent sections is 20 and Table 5 shows their characteristics. Likewise, Table 6 and Figure 5 summarize the comparison results between observed speeds and model speeds.

5. NEW DESIGN CONSISTENCY EVALUATION MEASURE

New measure was developed in this research considering the weakness found in existing models that mainly results from the inaccurate predictions of traffic accident occurrences when one simply uses the differences of speeds for successive highway sections as the consistency check variable.

It was found in this research that no apparent relationship between horizontal curve radii and traffic accident occurrences holds as shown in Figure 6 and 7. Even in cases where speed differentials between horizontal curves and long tangent sections were small, traffic accident occurrences were not so small. Figure 8 and Figure 9 show this problem. Later it was found that the most apparent indicator for explaining traffic accident occurrences was the difference of safe speeds and running speeds that can be obtained using the procedures developed in Section 3. This conclusion is supported by the graphs shown in Figure 10 and Figure 11.

It is to be noted that traffic accident occurrences were expressed by accident rates per million passing vehicles as well as EPDO's(Equivalent Property Damages Only).

6. IMPROVEMENT OF HIGHWAY DESIGN CONSISTENCY MODEL

Presently, the differences of speeds obtained between horizontal curves and long tangent sections have been used as the design consistency check measure and if speed differences are equal, it often is concluded that their levels of design consistency are the same. But, in reality, the same amount of speed difference may have completely different design consistency, as speed magnitudes can be different. In this regard, a new design consistency check measure (K) was developed in this research as in Equation (9).

$$K = \frac{V_S}{V_R} \cdot \Delta V \tag{9}$$

where,

V_S = safe speed on a horizontal curve (km/h)
V_R = estimated running speed on a horizontal curve (km/h)
ΔV = difference between running speed and safe speed (km/h)

Figure 12 and Figure 13 show relationships of K values and traffic accident patterns that were collected this research.

Design consistency, based on K values, can be categorized into three levels including less than or equal to 12, 12 to 17, and greater than or equal to 17. The labels for three levels are good, fair, and poor, respectively.

7. HIGHWAY DESIGN CONSISTENCY EVALUATION SOFTWARE

Figure 14 shows the output of design consistency software developed in this research. In practice, this software can be applied to find deficient highway sections. For example, in Figure 14, a deficient section represents a section of highway on which difference between running speed and safe speed is more than 25 km/h as, in Figure 10 and 11, highway sections with more than 25 km/h speed difference were found to be in poor condition.

8. CONCLUSIONS

Existing highway design consistency models were reviewed and model weakness was removed using more refined speed prediction models developed in this research. In contrast to the existing approach used for speed prediction, a stepwise approach was utilized for developing running speeds on horizontal curves and long tangent sections of highway. Results seem reasonable from traffic accident rate standpoint and it is recommended that highway consistency evaluation measure be replaced by K value, a combined measure of safe speeds and running speeds.

REFERENCES

b) Journals

Leisch, J., and Leisch, J., **New Concepts in Design-Speed Application,** Transportation Research Board, Transportation Research Record 631, Washington, D.C., 1977

Lamm, R., and Choueiri, E. M., **Recommendations for Evaluating Horizontal Design Consistency Based on Investigations in The State of New York,** Transportation Research Board, Transportation Research Record 1122, Washington, D.C., 1987

Lee, Seungjun, Lee, Dongmin, and Choi, Jaisung, **Evaluation of Geometric Design Consistency Based on Available Sight Distance,** Eastern Asia Society for Transportation

Studies, Journal of EASTS, 1999

c) Papers

Lee, Seungjun, Lee, Dongmin, and Choi, Jaisung, **Validation of the 10 mph Rule in Highway Design Consistency Procedure,** Transportation Research Board, 2nd International Symposium on Highway Geometric Design, Mainz, Germany, June 14-16, 2000

d) Other documents

Lee, Jeomho, **Evaluation of Highway Alignment Based on Design Consistency Analysis,** Ph.D. Thesis, University of Seoul, 2000

Table 1. The Result of Regression Analysis on Horizontal Curves

	$V_R = V_B\cdot(\alpha_0 + \alpha_1\cdot X_1 + \alpha_2\cdot X_2 + \alpha_3\cdot X_3^3)$			
	α_0	α_1	α_2	α_3
	1.0248	0.0670	-0.0028	-0.0919
t-statistic	67.160	1.906	-3.402	-4.483
$\text{t-statistic}_{(TABLE)}$	1.706			
F-ratio	8.79			
$\text{F-ratio}_{(TABLE)}$	2.98			
R^2	0.75			

Table 2. The Geometric and Environmental Conditions for surveyed Horizontal Curves

Site	Radius (m)	Lateral Clearance (m)	Lane Width (m)	Length of a exiting tangent section (km)	# of stop sign	# of access road and crosswalk
1	50	1.2	3.1	0.18	0	1
2	100	1.4	3.6	0.81	0	1
3	150	1.1	3.7	0.15	0	1
4	180	1.6	3.6	1.12	0	4
5	220	1.9	3.5	0.32	0	0
6	250	1.0	3.4	0.49	0	0
7	300	1.1	3.6	0.75	0	3
8	400	1.2	3.5	1.20	1	2
9	500	1.3	3.6	0.48	0	1
10	100	2.0	2.9	0.14	0	2
11	150	1.2	2.9	0.14	0	0
12	250	1.4	2.9	0.18	0	1
13	130	1.3	3.3	0.36	1	1
14	170	1.3	3.3	0.14	0	2
15	250	1.4	3.6	0.31	1	2
16	450	1.4	3.6	0.56	1	2
17	520	1.6	3.7	0.40	1	0

18	350	1.3	3.6	1.00	0	2
19	280	0.8	3.4	0.29	0	1
20	400	1.2	3.4	0.43	0	2
21	95	1.0	3.2	0.49	1	0
22	320	1.0	3.3	0.59	0	2
23	170	1.2	3.4	0.55	0	1
24	250	1.0	3.4	0.71	1	0
25	85	0.9	3.7	0.17	0	0
26	260	0.8	3.3	0.29	0	0
27	80	1.1	3.6	0.52	0	0
28	280	1.0	3.4	0.15	0	1
29	450	1.3	3.3	0.21	0	0
30	210	1.4	3.4	0.25	0	0

Table 3. Comparisons of Measured Speeds and Estimated Speeds on Horizontal Curves

Site	Friction Factor	Driver's Reaction Time	α_0	α_1	α_2	α_3	Measured Speed (km/h)	Estimated Speed (km/h)
1	0.68	1.0 sec	1.025	0.067	-0.092	-0.003	53.4	56.9
2	0.60						73.8	74.1
3	0.52						72.9	74.3
4	0.47						70.6	70.2
5	0.42						80.0	82.4
6	0.39						77.2	76.7
7	0.34						73.6	73.6
8	0.31						75.2	76.5
9	0.29						80.2	85.3
10	0.60						69.7	71.3
11	0.52						75.3	72.1
12	0.39						69.2	76.2
13	0.55						67.6	67.2
14	0.48						75.1	73.3
15	0.39						69.2	71.0
16	0.30						72.2	76.2
17	0.29						78.8	80.8
18	0.32						80.5	81.7
19	0.36						78.8	73.8
20	0.31						82.1	79.2
21	0.61						64.8	61.8
22	0.33						78.8	75.2
23	0.48						72.4	76.3
24	0.39						75.6	71.1
25	0.62						66.5	65.5
26	0.38						77.2	73.7
27	0.63						69.1	67.2

28	0.36						78.8	74.8
29	0.30						82.1	81.7
30	0.41						74.0	76.4

Table 4. Result of Regression Analysis on Tangent Sections

	$V_R^T = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \beta_3 \cdot X_2^2 + \beta_4 \cdot X_2^3$				
	β_0	β_1	β_2	β_3	β_4
	78.2827	19.0260	-7.3689	2.4262	-0.0678
t-statistic	58.261	5.762	-3.261	2.789	-3.047
t-statistic$_{(TABLE)}$	1.753				
F-ratio	9.15				
F-ratio$_{(TABLE)}$	3.06				
R^2	0.71				

Table 5. Geometric and Environmental Conditions on Tangent Sections

Site	Length of a tangent section (km)	# of stop sign, access road and crosswalk
1	1.20	5
2	0.63	2
3	0.28	2
4	0.25	4
5	0.49	2
6	0.36	1
7	0.46	1
8	0.45	1
9	0.53	0
10	0.50	1
11	0.28	4
12	1.03	5
13	0.55	2
14	0.71	3
15	0.33	1
16	0.32	1
17	0.16	0
18	0.15	0

19	0.14	0
20	0.14	1

Table 6. Comparison of Measured Speed and Estimated Speed on Tangent Sections

Site	β_0	β_1	β_2	β_3	β_4	Measured Speed (km/h)	Estimated Speed (km/h)
1	78.2827	19.0260	-7.3689	2.4262	-0.0678	81.6	82.6
2						85.0	84.2
3						77.2	77.5
4						75.6	75.0
5						77.2	81.5
6						80.0	80.0
7						78.6	82.0
8						78.0	81.8
9						88.1	88.4
10						86.7	82.8
11						74.4	75.6
12						80.5	79.3
13						86.0	82.7
14						86.9	86.0
15						82.1	79.6
16						78.8	79.4
17						80.5	81.3
18						81.3	81.1
19						82.1	80.9
20						77.2	75.9

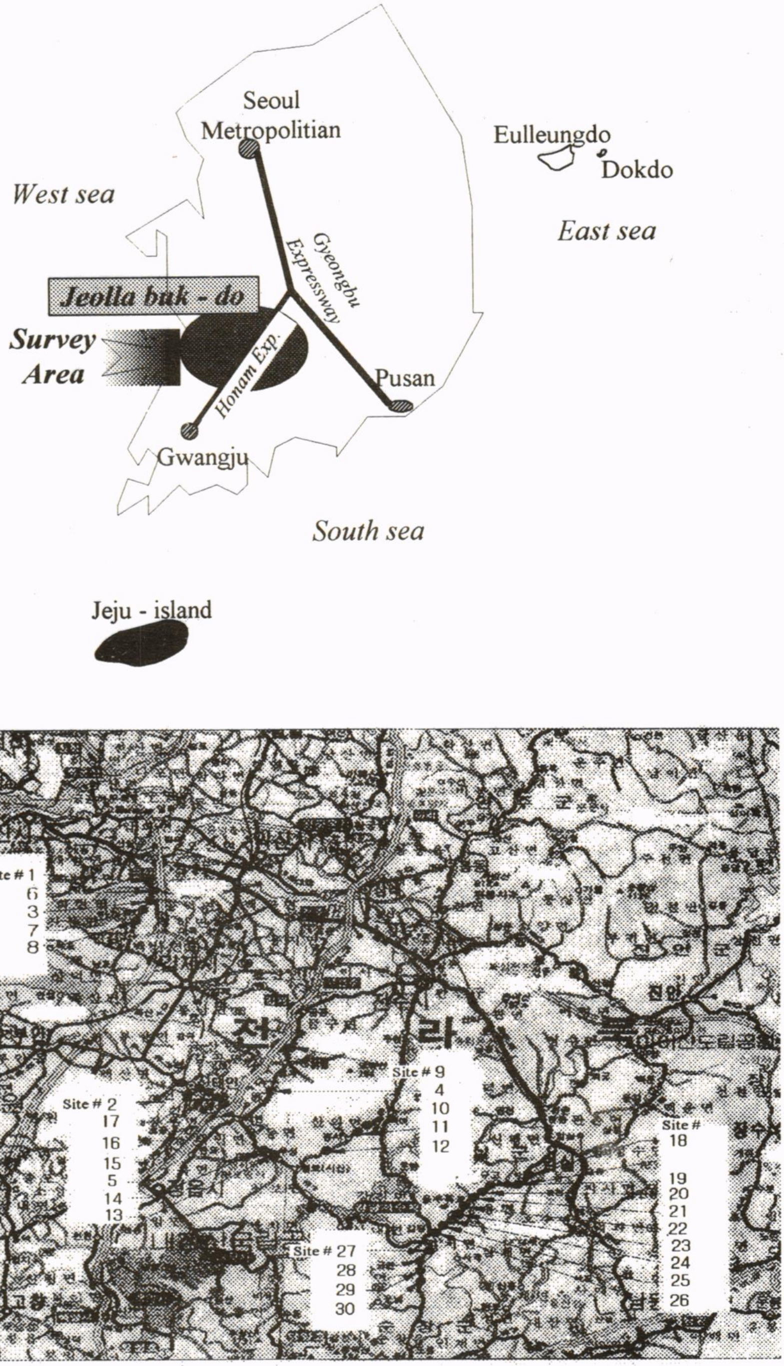

Figure 1. Location of Data Collection Sites.

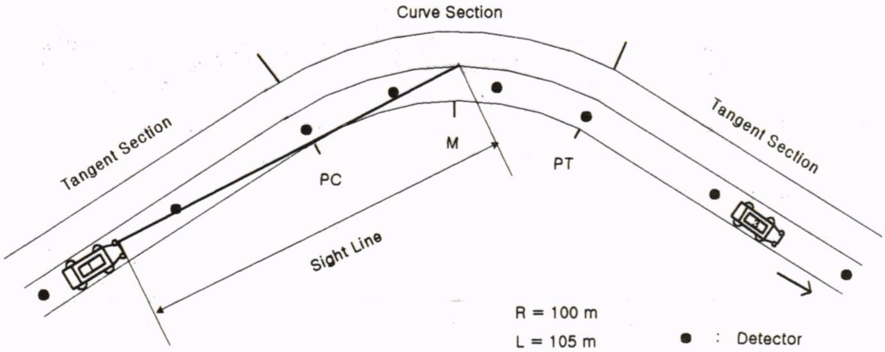

Figure 2. Location of Installed Detector on a Horizontal Curve.

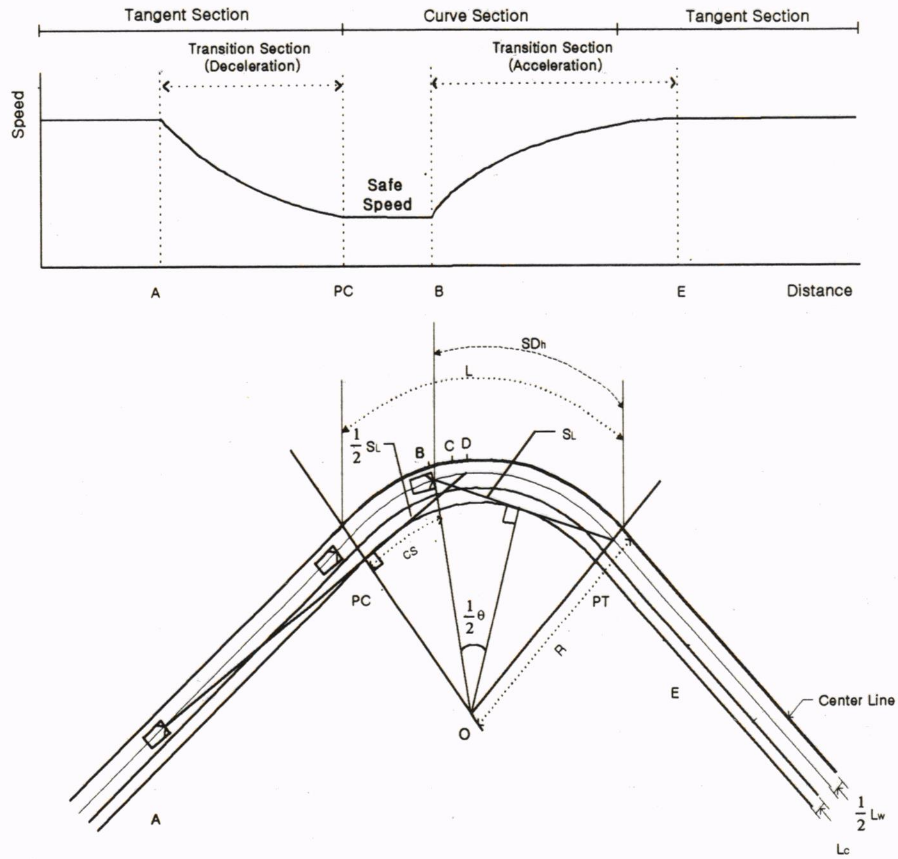

Figure 3. Sight Distance and Safe Speed Diagram on a Horizontal Curve.

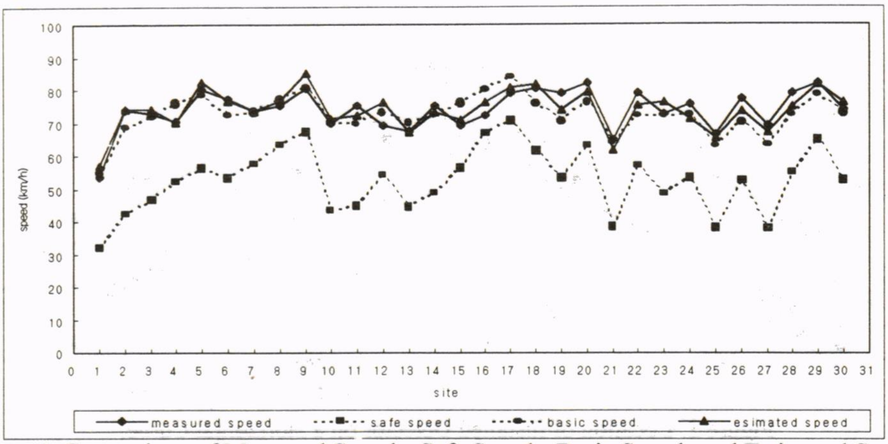

Figure 4. Comparison of Measured Speeds, Safe Speeds, Basic Speeds and Estimated Speeds on Horizontal Curves.

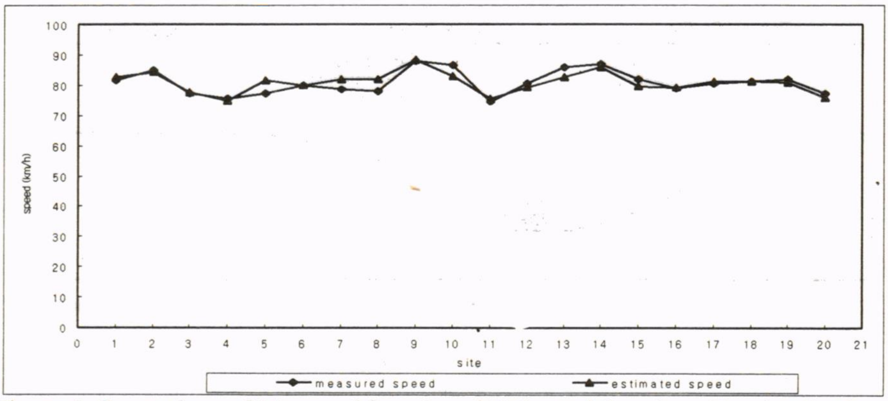

Figure 5. Comparison of Measured Speeds and Estimated Speeds on Tangent Sections.

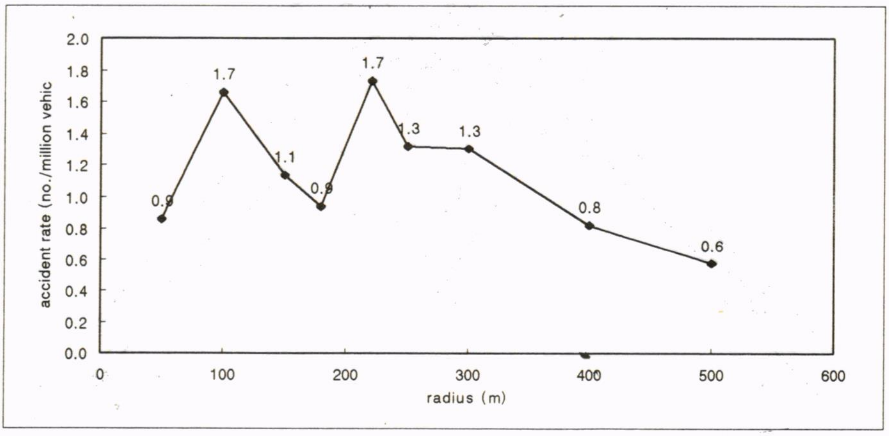

Figure 6. Radius-Accident Rate Relationships.

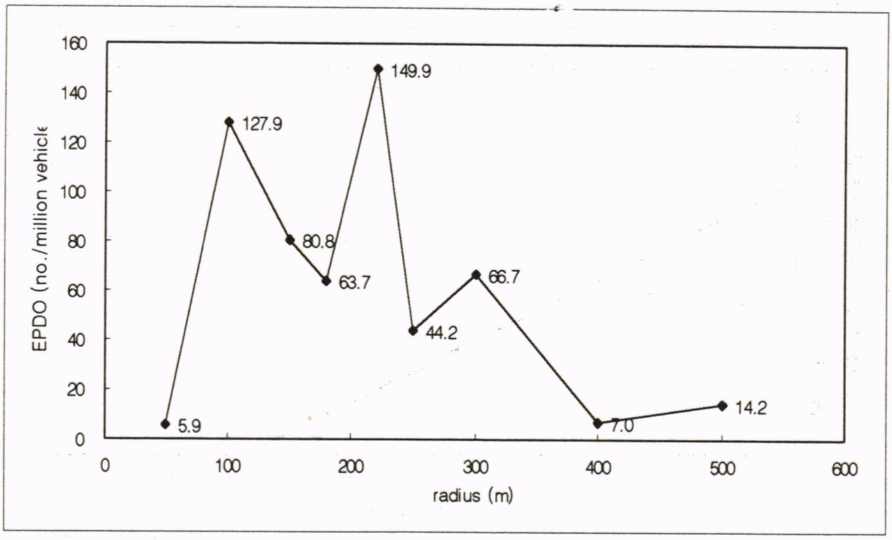

Figure 7. Radius-EPDO Relationships.

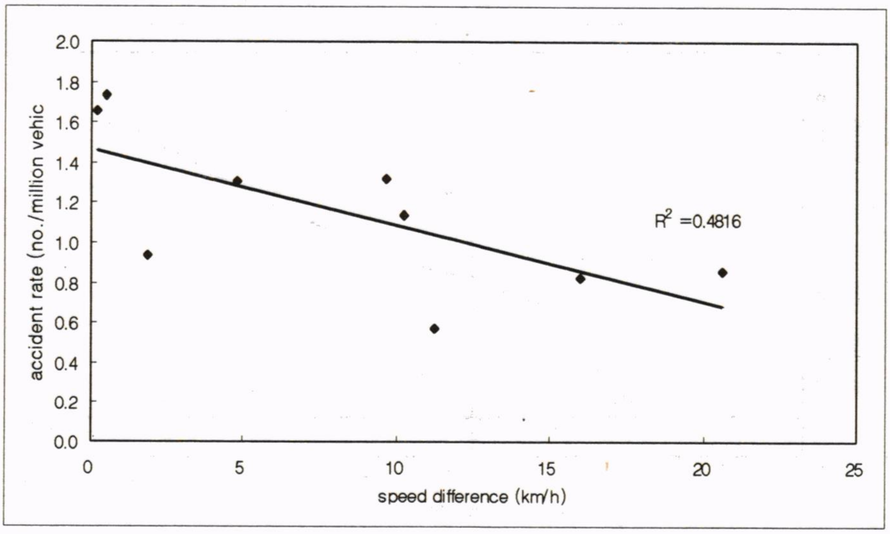

Figure 8. Difference Between Running Speeds on both Tangent Section and **Horizontal** curve-Accident Rate Relationships.

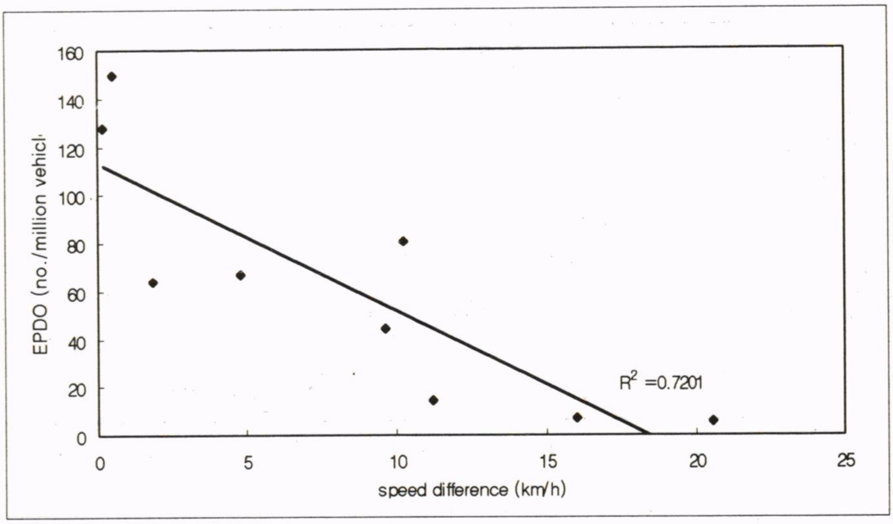

Figure 9. Difference Between Running Speeds on both Tangent Section and **Horizontal** curve-EPDO Relationships.

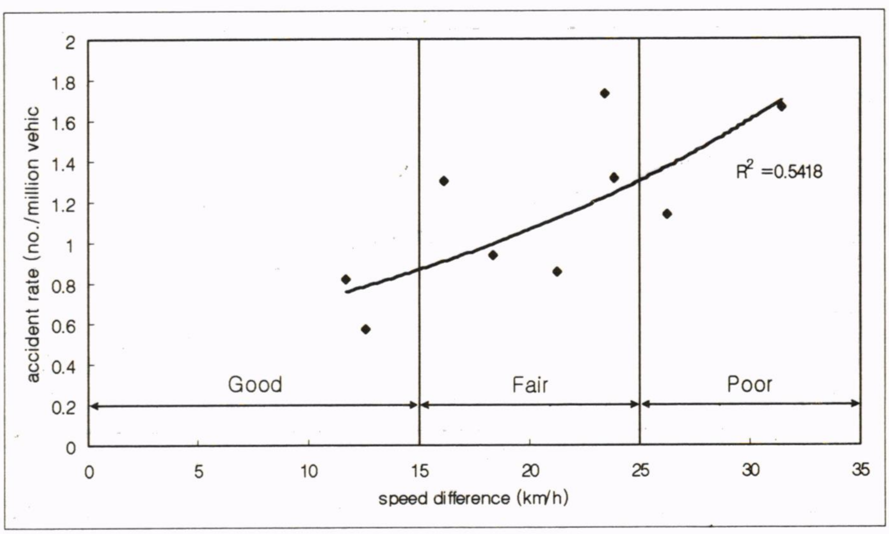

Figure 10. Difference Between Running Speed and Safe Speed on a Horizontal curve-Accident Rate Relationships.

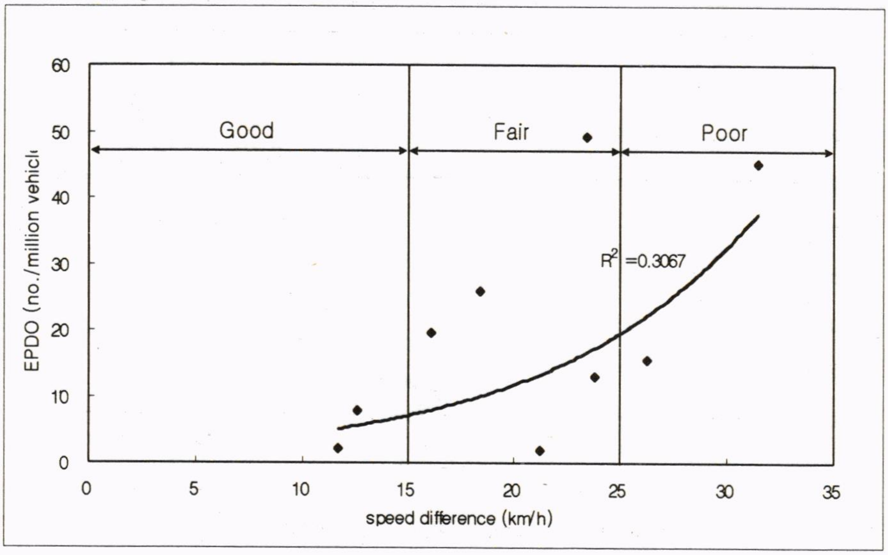

Figure 11. Difference Between Running Speed and Safe Speed on a Horizontal curve-EPDO Relationships.

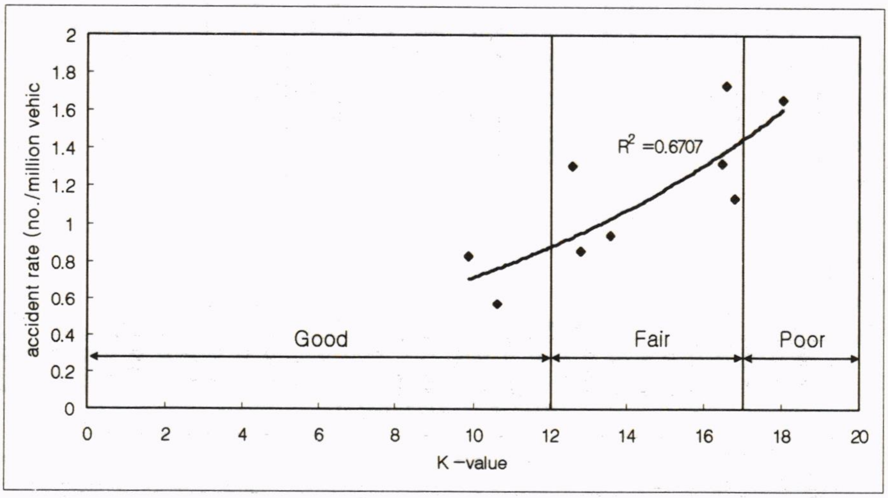

Figure 12. K Value-Accident Rate Relationships.

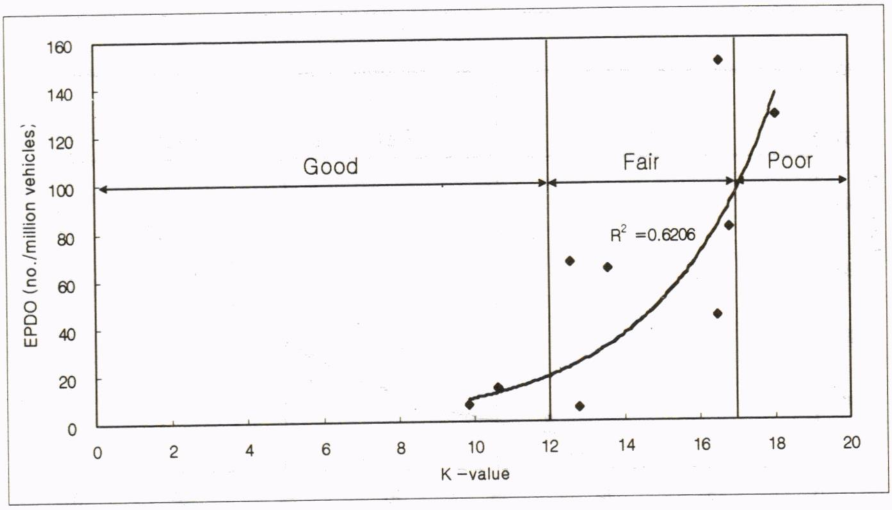

Figure 13. K Value-EPDO Relationships.

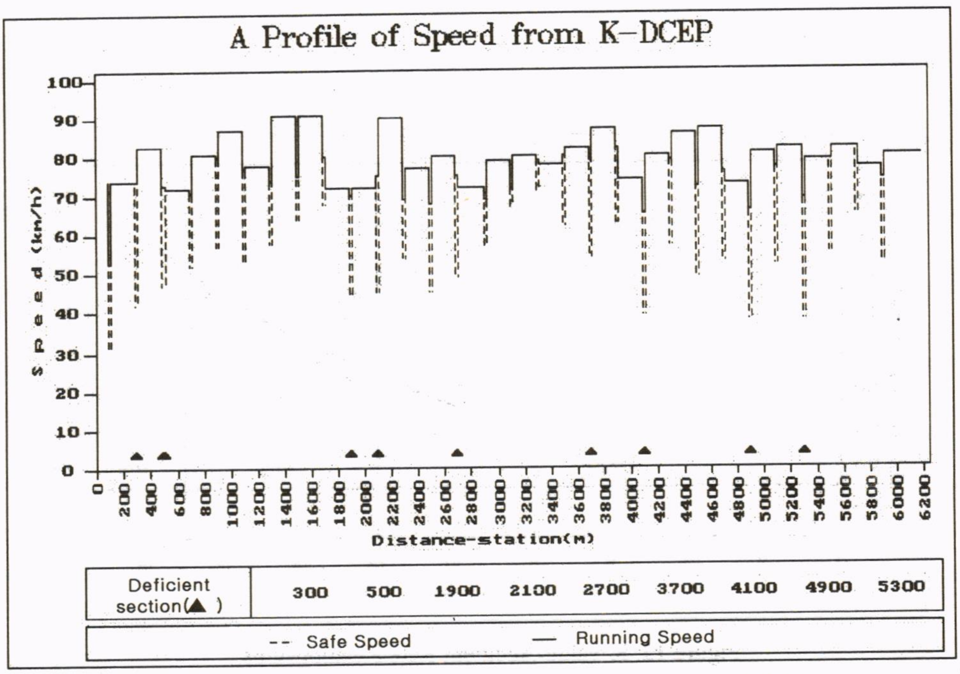

Figure 14. Result of Design Consistency Software, K-DCEP.