EVALUATION OF GEOMETRIC DESIGN CONSISTENCY BASED ON AVAILABLE SIGHT DISTANCE

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Abstract: The objective of this study was to develop a new speed calculation procedure for evaluating highway geometric design consistency. This procedure has the capability of reflecting the effect of driver's available sight distance into determining drivers' running speeds. The main interest of the study was to calculate the vehicle running speeds for isolated horizontal curves, short tangent segments between two continuous horizontal curves and horizontal curves combined with vertical grades. The main concept in speed calculation was that drivers would travel with the speeds determined by checking the available sight distance provided at each highway segment. Field surveys were made in the horizontal curve sites and the calculated speeds seemed to be in a good agreement with the field speed data. From this, it was believed that the new procedure could produce realistic running speeds, which may be utilized when one wants to check the highway geometric design consistency, a vital tool in analyzing the appropriateness of a highway plan and profile drawings.

1. INTRODUCTION

1.1 Background and Objectives

In highway alignment design, it is necessary to understand the user satisfaction for the given alignment, which usually is expressed in terms of operational and safety. The present highway design process simply focuses on meeting the required design standards, which are specified in the highway alignment design manual, the AASHTO Green Book for example. Problem is that these design standards mostly hinge on the design speed, which is selected subjectively by the designers. Once the design speed is determined, it controls the subsequent design process and, because of this power of design speed, they used the terminology of design speed concept from its inception of 1940's in the US. For decades, however, it has been argued that the highway design concept, which assumes drivers' speeds are constant values falling within 80-90 % of design speed, tends to oversimplify drivers' speed determining process. Thus, because of the speed discrepancy, rather unsafe conclusions for the given highway alignment are sometimes made. Moreover, presently, highway designers seem to be preoccupied with the design speed concept and do not seem to consider other important aspects of highway alignment such as drivers' comfort, workload and expectancy. It is required for highway designers to understand drivers' speed determining process for given curve radius, curve length,

superelevation, side friction and vertical grades.
For this, the design consistency concept was proposed decades ago. The design consistency can be defined as the avoidance of abrupt changes in geometric features for continuous highway elements and the use of design elements in combination that meet driver expectancies. This concept is used to check drivers' safety along a highway segment based on the values of predetermined traffic flow variables such as operating speed, delay, and so forth. In this study, speed-profile analysis was applied to check the design consistency. J. Leisch developed this idea based on the premise that a significant amount of speed change would impair drivers' expectancy to the extent that safety can be violated. However, his idea was limited to its macroscopic speed estimation process, which often was unresponsive to the change of highway alignment. A more accurate speed calculation method has been in need for years.

The main interests of this study were to develop a new procedure for calculating drivers' running speeds along a road, in a microscopic manner, so that the effects on running speed of several geometric conditions variables including curve radius, lateral clearance, side friction factor and grade were carefully analyzed. Field studies were made to validate the developed procedure and computer software was generated to minimize calculation efforts and to graphically demonstrate the running speeds along the given highways.

2. MODEL DEVELOPMENT

The following assumptions were made in this study.

- Drivers decelerate when available sight distance is less than the one for the current running speed. They accelerate to their desired speeds when the sight distance gets longer. The deceleration rate depends on the sight distance increase.
- Acceleration depends primarily on vehicle performance capability. Even if sight distance increases rapidly, the acceleration can be constrained by vehicle performance.

2.1 Tangent Section

On tangent sections of highway, drivers want to maintain the desired speed, a speed dependent upon individual drivers and different from the design speed. In this study, 80km/h was selected. When one wants a site-specific value, data collection should be made.

2.2 Horizontal Curve Section

The speed calculation procedure on horizontal curve sections can be summarized as:
- Determination of the sight distance and corresponding vehicle running speed on an isolated horizontal curve
- Location of the beginning point of deceleration entering a curve
- Location of the ending point of acceleration exiting a curve
- Determination of the running speed on a short tangent section located between two successive curves. The desired speed can not be obtained in this case.
- Determination of the running speed for the combination of horizontal and vertical alignment

The following sections explain the details for each of the above.

1) An Isolated Horizontal Curve

(1) Minimum Available Sight Distance and Running Speed

As was shown in Figure 1, the minimum available sight distance occurs when entering a curve section. On the section between PC and point E, the sight line exists within the curve length and the minimum available sight distance equals to the minimum stopping sight distance. As vehicle's passing the point E, the available sight distance gets increasing.

The following describes how the running speed was determined in this case based on the available sight distance.

i) Inner lane

$$S_L = 2\sqrt{(R-1.8)^2 - (R-5.4)^2} \tag{1}$$

where,
S_L = the available sight line on a curve (m)
R = radius of a curve (m)
1.8 = one half of lane width (m)
5.4 = lane width (3.6m) + lateral clearance(1.8m)

ii) Outer lane

$$S_L = 2\sqrt{(R+1.8)^2 - (R-3.6)^2}$$

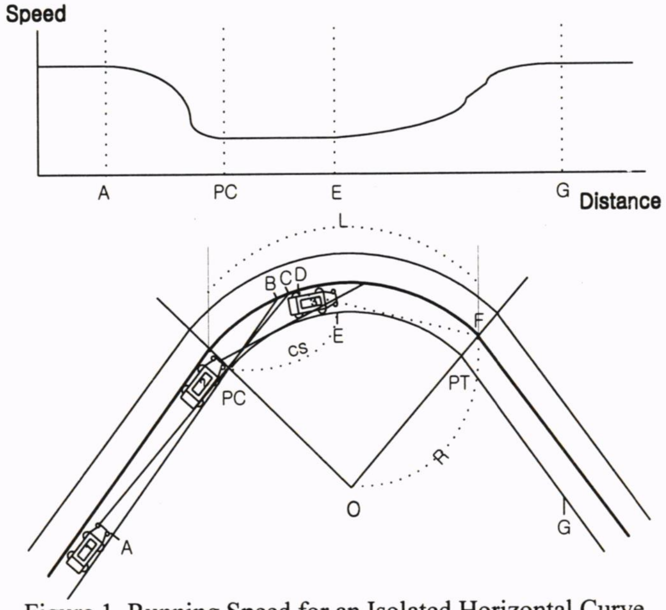

Figure 1. Running Speed for an Isolated Horizontal Curve

The available sight line(S_L)in equation (1) is determined as follows:

$$S_L = 2(R-1.8)\sin\frac{\Theta}{2} \tag{2}$$

where,
θ = central angle(degree)

Hence,

$$\Theta = 2\sin^{-1}\left[\frac{S_L}{2(R-1.8)}\right] \tag{3}$$

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

$$SD_h = \frac{(R-1.8)\pi\Theta}{180} \tag{4}$$

Also, the minimum stopping sight distance on a curve ($MSSD_h$) is:

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

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

Thus the running speed in equation (5) can be obtained as follows:

$$V_h^2 + 2g(f \pm G)tV_h - 2g(f \pm G)SD_h = 0$$

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

Also, the length on a curve where the available sight distance remains constant is:

$$cs = L - SD_h \tag{7}$$

where,
cs = length on a curve where the minimum sight distance remains constant (m)
L = curve length (m)

The friction factors, f, used on the above procedure and specified in the AASHTO manual, are shown in Table 1.

Table 1. Coefficients of Friction Factor for Determining Running Speed on a Curve

Design Speed(km/h)	Coefficients of Friction(f)	Minimum Curve Radii(m)
120	0.28	710
100	0.29	460
80	0.30	280
70	0.31	200
60	0.33	140
50	0.35	90
40	0.38	60
30	0.40	30

(2) Point of Deceleration Entering a Horizontal Curve

When a driver enters a curve with a desired speed, the minimum stopping sight distance for the desired speed is:

$$MSSD_d = tV_d + \frac{V_d^2}{2g(f \pm G)} \tag{8}$$

where,
$MSSD_d$ = minimum stopping sight distance based on desired speed (m)
V_d = desired speed (m/s)

$MSSD_d$ is the distance from point A to point C in Figure 1, and can be approximated as the distance from A to B. The distance required for deceleration is as follows:

$$S_{dec} = MSSD_d - \frac{1}{2} S_L \tag{9}$$

where,
S_{dec} = deceleration distance entering a curve(m)

As shown in Figure 1, a driver entering a curve from a tangent section checks if the available sight distance gets reduced, and, if so, the driver decelerates until a safe speed for the provided sight distance is reached. Inside a curve, where the available sight distance does not change, the driver keeps a constant speed.

(3) Point of Acceleration Termination Exiting a Curve

Point G in Figure 1 is the point where a driver, exiting a curve section where the available sight distance is limited, reaches the desired speed. At this point, the driver will stop acceleration. Defining average acceleration as A_{cc}, the distance between a point E inside the curve to point G is as follows:

$$S_{acc} = \frac{V_d^2 - V_h^2}{2A_{cc}} \tag{10}$$

where,
S_{acc} = distance between the point with curve speed and the point with desired speed (m)
A_{cc} = average acceleration rate (m/s^2)

It is natural that acceleration should be showing a non-linear pattern, as was the case for deceleration. And, as acceleration tends to be less than the deceleration, the acceleration distance was longer. It is to be noted that as a vehicle exiting a curve is provided an adequate sight distance even before it reaches PT, it accelerates even inside the curve.

2) A Short Tangent Section Between Two Horizontal Curves

Drivers reach the desired speed only when tangent sections are relatively long. If a tangent section is located between two horizontal curves, it is impossible for the drivers to reach the desired speed. Thus, in this case, vehicle speed should be determined separately based on the available sight distance and vehicle's acceleration capability. Figure 2 illustrates the case.

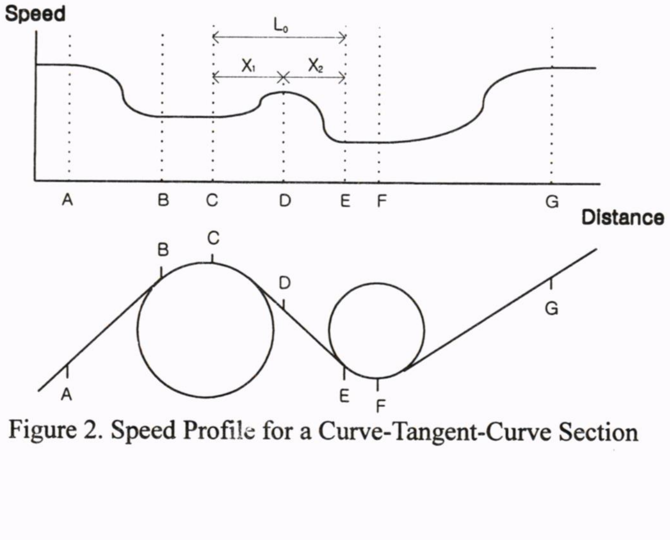

Figure 2. Speed Profile for a Curve-Tangent-Curve Section

To find the maximum speed on the tangent section between two horizontal curves, the following equations were used.

$$L_0 = X_1 + X_2 = SD_{h1} + L_t \tag{11}$$

Hence,

$$X_1 = L_0 - X_2 = (SD_{h1} + L_t) - (SD_{vs} - \frac{1}{2}SD_{h2}) = (SD_{h1} + \frac{1}{2}SD_{h2} + L_t) - SD_{vs}$$

Therefore,

$$X_1 = \frac{V_s^2 - V_{h1}^2}{2A_{cc}} = (SD_{h1} + \frac{1}{2}SD_{h2} + L_t) - [tV_s + \frac{V_s^2}{2g(f \pm G)}] \tag{12}$$

where,
L_0 = acceleration/deceleration distance from C to E (m)
X_1 = acceleration distance (m)
X_2 = deceleration distance (m)
L_t = distance of the tangent section (m)
SD_{h1} = minimum available sight distance for the previous curve (m)
SD_{h2} = minimum available sight distance for the following curve (m)
SD_{vs} = available sight distance at the point with full acceleration exiting the previous curve (m/s)
V_s = maximum speed on the tangent section (m/s)

Equation (12) can be rewritten as:

$$V_s^2 + \frac{2A_{cc}g(f \pm G)t}{[A_{cc} + g(f \pm G)]}V_s$$

$$-\frac{2A_{cc}g(f \pm G)}{[A_{cc} + g(f \pm G)]}(SD_{h1} + \frac{1}{2}SD_{h2} + L_t) - \frac{g(f \pm G)V_{h1}^2}{[A_{cc} + g(f \pm G)]} = 0 \tag{13}$$

For simplification, the following expression for equation (12) was used:

$$V_s^2 + bV_s + c = 0$$

3) Combination of Horizontal and Vertical Alignment

A separate calculation needed to be made to reflect the effects on running speed of horizontal curve on vertical grade. In horizontal curve on vertical grade, gradient value is added to equation (6), while horizontal curve on level terrain has not the effect of grade. The predicted speed of horizontal curve on level terrain is higher than that on downgrade but is lower than that on upgrade because the minimum stopping sight distance is affected by gradient. Therefore the speed of horizontal curves that have same radius is changed according to gradient. The speed prediction results are explained in the next chapter.

3. MODEL VALIDATION

The following three steps were followed to validate the speed calculation procedure developed in this study.

- Field study was made to collect the speed data on horizontal curves, which have 25 – 625 meter radius. Also, comparisons were made with the predicted speed for the surveyed curves.
- Acceleration were surveyed for the above horizontal curves
- For a test highway alignment, the model speed was compared with the speeds resulted from the present AASHTO design method. To facilitate the computational procedure,

a computer software using C was written in this study.

The following sections elaborate the above procedures.

3.1 Comparison of Calculated Speeds with the Field Survey Speeds

Table 2 and Figure 3 are the comparison results. The measured speeds are averaged from the speed of vehicles that are not included in the platoon. Here, it can be ascertained that the calculated speeds fairly well replicated the field speeds. The survey also showed that the vehicle speeds reached approximately 62 km/h and did not change much. The design speed is also indicated in Figure 3.

Table 2. Comparison of Model Speeds with Field Survey Speeds

Curve Radii (m)	Calculated Speeds (km/h)	Measured Speeds (km/h)
25	27.5	31.5
55	36.6	36.8
75	40.8	48.3
170	52.2	54.2
250	58.1	61.0
310	62.3	59.0
350	64.9	58.0
440	68.9	61.7
625	76.0	61.6

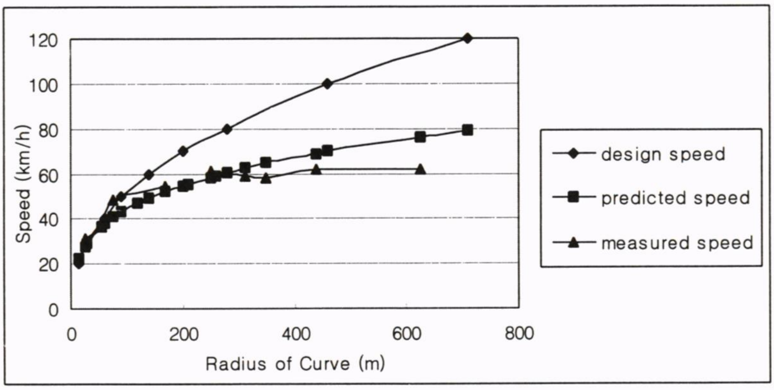

Figure 3. Fluctuation of the Calculated Speeds for Various Curve Radii

3.2 Average Acceleration

Although the acceleration of vehicles is various according to drivers, the average acceleration rate was used in the speed prediction. The acceleration rates on horizontal curve sections were adapted according to curve radius and shown in Table 3 and Figure 4.

Table 3. Collected and Used Average Accelerations in this Study

Radius(m)	Acceleration Rates(m/s^2)
≤ 60	0.54
≤ 90	0.47
≤ 140	0.38
≤ 210	0.31
≤ 280	0.25
> 280	0.20

3.3 Comparison of the Calculated Speeds with the AASHTO Speeds

For a better comparison, a relatively simple test highway alignment was proposed as shown in Table 4 and Figure 5 and 6. On this test highway alignment, two types of speeds, one by the proposed method and the other from the AASHTO method, were analyzed. For AASHTO method, design speed of 70km/h was applied and the geometric conditions were designed in accordance with the design standards.

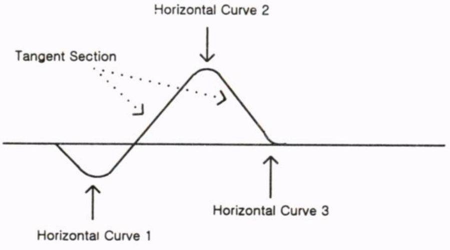

Figure 4. Test Horizontal Alignment.

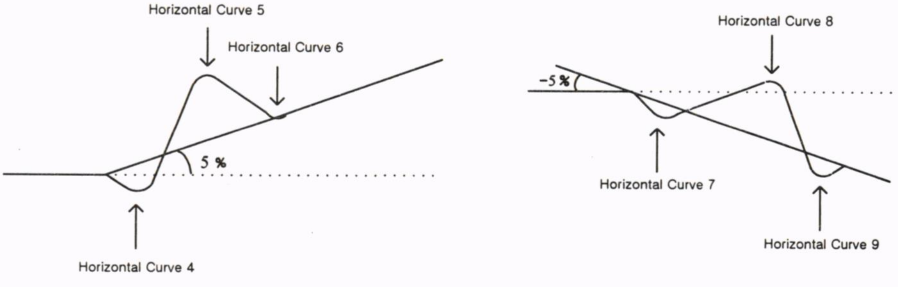

Figure 5. Combination of Horizontal and Vertical Alignment

Table 4. Geometric conditions of the Test Alignment

Curve	Curve Radius(m)	Curve Length(m)	Gradient (%)	Average Acceleration Rate(m/s^2)
C-1	280	200	0	0.25
C-2	200	120	0	0.31
C-3	210	120	0	0.31
C-4	280	200	5	0.25
C-5	200	120	5	0.31
C-6	210	120	5	0.31
C-7	280	200	-5	0.25
C-8	200	120	-5	0.31
C-9	210	120	-5	0.31

Table 5 and Figure 6 show the predicted speeds. As mentioned earlier, the software to show graphically the calculated speeds was developed in this study. Figure 6 is an example of computer output.

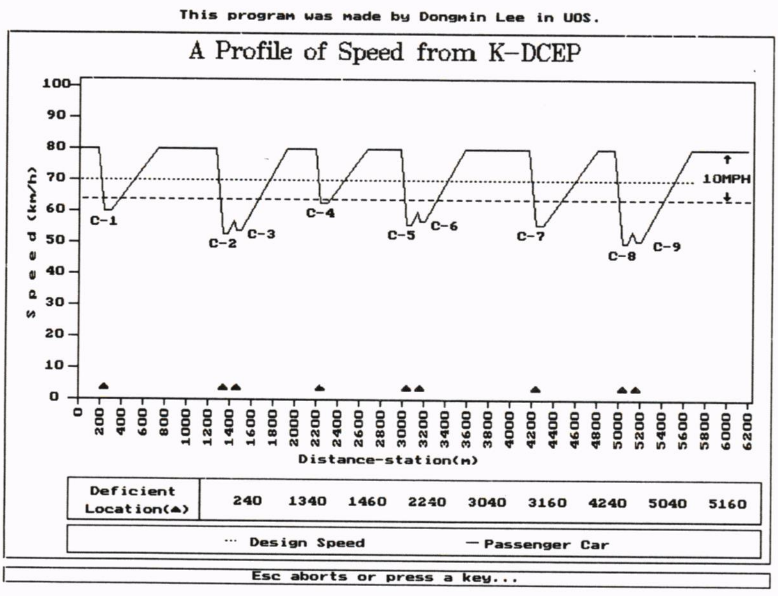

Figure 6. Speed-profile Analysis Made by the Proposed Method
(Generated by the Software Developed in this Study)

Table 5. Speed Prediction Results for the Test Alignment

Curve ID	Entering Speeds (km/h)	Curve Speeds (km/h)	Exiting Speeds (km/h)	Curve characteristics
C-1	80.0	60.3	80.0	Isolated curve
C-2	80.0	54.0	57.5	A short tangent section
C-3	57.5	54.8	80.0	
C-4	80.0	63.6	80.0	Isolated curve
C-5	80.0	56.8	60.2	A short curve section
C-6	60.2	57.7	80.0	
C-7	80.0	56.5	80.0	Isolated curve
C-8	80.0	50.7	54.4	A short curve section
C-9	54.4	51.5	80.0	

In comparison with the predicted speed and the design speed, the predicted speed vary along the highway, while the design speed does not change for all highway segments. In the Figure 6, the predicted speed becomes desired speed, 80km/h, on tangent section but becomes lower on curve sections than design speed, despite the geometric condition of the curves meet the design standards of design speed, 70km/h. This suggests that, even though the AASHTO method was most suitable to the design speed concept, drivers did not behave as the design speed concept assumes. Most drivers want the highway alignment to be designed consistently and the running speed not to be changed abruptly. In order to check the deficient locations, 10mile/h range was used as criterion. In Figure 6, these deficient locations are indicated by triangle.
The inconsistent highway design brings about a rapid speed change. The rapid speed change on a road is reported to be the reason why traffic accidents increase. Therefore, for checking plan and profile drawings submitted for approval prior to construction, the speed-profile analysis, such as the one developed in this study, is suggested to be used. By doing so, it is expected that the reviewing panel's reliability will increase significantly.

4. CONCLUSION

The following conclusions were made in this research:

- The AASHTO design method, that involves the design speed concept, should be used with a caution when highway alignment varies significantly, as vehicle running speeds for the alignment generally are very sensitive to highway geometric conditions. The speed-profile analysis developed in this study can be used as a tool for identifying deficiency highway sections.
- The calculated speed based on the proposed method in this study can be used to improve the accuracy of Leisch's speed-profile analysis

The following topics are required to be studied in the future research:

- More accurate calibration of acceleration and deceleration rates according to curve

characteristics and vehicle types.
- Desired speeds for various ranges of highway alignments.
- Speed predictions associated with various vehicle types.
- Integration of the proposed method with a computerized highway alignment

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