EVALUATION OF HIGHWAY GEOMETRIC DESIGN AND ANALYSIS OF ACTUAL OPERATING SPEED

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Abstract: The purpose of this study is to evaluate the actual highway geometric design properly, and propose a well-balanced design policy especially considering the drivers perception and behavior. In this paper, after classification of all the design elements, the new concept of 'reversely calculated speed' as an evaluator of road alignment is introduced and examined. The analysis of the 'reversely calculated speed' for actual alignments on Expressways in Japan shows the drivers' perception of physical limitation given by road alignment. Then the actual operating vehicle speed is estimated and analyzed using database of vehicle detectors. Using the five-minutes mean speed, with only one passenger car, observed by detectors in the median lane on more than 7,000 km networks of Expressways in Japan, the speed running absolutely independent can be assumed as an 'operating speed' (free speed) reasonably. At last, the values of operating speed are evaluated with highway design elements such as curvature of horizontal radius and vertical grade.

Key Words: highway geometric design, operating speed, drivers' perception and behavior

1. BACKGROUND AND PURPOSE

Highway geometry should be designed for vehicle traffic safety and efficiency, particularly on the trunk roads or Expressways on which traffic function must be most important. Though the design policy was established, the prerequisites of design have been imaginary or extremely limited. For example, minimum radius of horizontal curve is defined with design speed, superelevation and side slip friction factor. The value of the side slip friction factor used in any design standards, such as AASHTO Green Book (AASHTO, 2001) is not clearly determined with changes according to the road surface condition, such as dry, wet, or snowy surface. The authors insist that all of the design values should have a unique safety factor to keep consistent traffic safety.

The actual operating speed must correspond to something to the road design elements. There had been several estimation models of operating speed, but it did not work well to be used for design purpose of road geometry, or did not calibrated enough because of the difficulty of data acquisition. Such an estimation model should have a feature including drivers' perception and behavior.

The purpose of this study is to evaluate the actual highway geometric design properly, and propose a well-balanced design policy especially considering the drivers perception and behavior. Figure 1 shows the concept and structure of this study. The consistency is "the conformance of a highway's geometric and operational features with driver expectancy"(NCHRP, 2003). Therefore, the consistency of 'speed potential' and actual
operating speed should be achieved under the proper design policy. The 'speed potential' includes physical limitation such as actual physical road geometry, safety factor and drivers' comfort factors. In this paper, 'reversely calculated speed' is introduced as one of the indicator of this 'speed potential'. Actual operating speed should be affected by many factors; factors in internal environments (driver condition, vehicle performance, load condition, etc.), in external environments (road alignments, number of lanes, posted speed, traffic condition, sight distance, etc.), and weather conditions (dry, wet, or snowy surface, foggy scenery condition, heavy rain, etc.). Finally, this study is aimed at developing an estimation model of actual operating speed with any given highway geometric design condition, in consideration of drivers' characteristics of their perception and behavior in the future.

In this paper, after classification of all the design elements, the new concept of 'reversely calculated speed' for an evaluator of road alignment is introduced and examined. Then the actual operating speed is estimated using the database of vehicle detectors on Expressways in Japan. At last, the estimated values of actual vehicle speed are evaluated with highway design elements such as curvature of horizontal radius and vertical grade.

2. CLASSIFICATION OF DESIGN ELEMENTS

2.1 Japanese Highway Design Standards

In Japan, 'Road Geometry Ordinance' (with 'enforcement detailed regulations') was enacted in
1970 based on the 'Road Law', and the ordinance and the detailed regulations are revised several times, but still the basic concept of the ordinance is not changed at all. In this ordinance, the important geometric design elements are declared, and some of the elements are with standard dimensions in the text of it. Those standard dimensions are enacted in the text of the ordinance therefore there is little room to discuss for modification in any actual design practices. But in the engineering sense, the standard dimensions should be examined continuously with the change of the era; from the dawn era of the motorization to the expansion era, from the expansion era to the maturity era, and so on.

In this chapter, such standards written in the text of the ordinance are re-examined and classified from the view points of engineering sense. Through examination of safety factors, the authors aim at developing unified safety factors, which correspond to the equal condition of traffic operation, for any design elements.

2.2 Four Types of the Standard Regulations

In the 'Road Geometry Ordinance', the authors insist that all of the standard regulations can be classified into four categories as below;
A. Unique regulation values are provided,
B. The minimum values are provided,
C. The maximum values are provided, and
D. Standard values are provided.

An example of the category A is the lane width. The dimensions of lane width are determined as a unique value ranging from 2.75[m] to 3.5[m] depending on the road classes and grades. An example of the category B is the median width. Only the minimum values of the median widths are determined such as from 1.0[m] to 4.5[m] depending on the road classes and grades, and space limitation conditions. An example of the category C is composed slopes of the cross slopes and vertical grades. The maximum values of the composed slopes are determined as from 10.0[%] to 11.5[%] (except for snowy and chilly area) depending on the road environment and traffic conditions. An example of the category D is the width of 'green area'. The text in the ordinance just provides the standard value of this width such as 1.5[m].

There are 30 main design elements written in the ordinance. Among them, there are 5 major elements about lanes, 7 elements about shoulders, 3 elements about cross slopes, 9 elements about road alignments, and 7 elements for the other road sections than ordinary sections. Therefore, the number of major design elements for ordinary sections is 23.

2.3 Re-arranged Classifications

From the view points of engineering sense, major 23 design elements can be classified into different four types; such as (1) Compulsory Standards, (2) Necessary Conditions, (3) Advisable Dimensions, and (4) Standard proposals.

(1) Compulsory Standards: the elements classified into this type are very important for securing any drivers or vehicles against physical limitation of road surface and vehicle tires. This type of design elements is as a compulsory to secure safety of any vehicles running with design speed. The minimum stopping sight distance, the minimum horizontal radius,
minimum radius of crest vertical curves, and maximum superelevation in horizontal curve should be classified into this type.

(2) Necessary Conditions: The elements classified into this type are required to enable any vehicles to move in the speed corresponding to the design speed at the roadway sections. This condition is affected by the vehicle performance under consideration. The maximum vertical grades are typically classified into this type.

(3) Advisable Dimensions: The dimensions of design elements classified into this type written in the ordinance offer the comfortable driving environments at the speed of design speed. Many elements in this type is classified into this type; lane widths, minimum median widths, climbing lane widths, frontage road widths, minimum shoulder width (left- and right-shoulders), stopping area widths, cross slopes, minimum length of transient spiral, minimum length of vertical curve sections, minimum radius of vertical sag curves, etc.

(4) Standard Proposals: A standard dimension of a design element is proposed in the text of the ordinance to present just one value, for practical purpose for convenience to practitioner of road design engineers. The width of green area would be the example of this type of design standard.

2.4 Design Policy of Compulsory Standards

The design elements classified into the type of 'Compulsory Standards' are most important to design roads especially for safety reason. The four elements, the minimum stopping sight distance, the minimum horizontal radius, the minimum radius of crest vertical curves, and maximum superelevation in horizontal curves, are included.

The dimensions of the minimum horizontal radius and maximum superelevation in horizontal curvature sections have an interaction each other, and depend on side friction factor, speed. The equation (1) shows the well-known relationship same as AASHTO Green Book (AASHTO, 2001).

\[ R \geq \frac{v^2}{g(f_L + i)} \]  

where,  
\[ R: \text{horizontal radius [m]}, \]
\[ v: \text{vehicle speed [m/s]}, \]
\[ g: \text{gravity acceleration [m/s}^2], \]
\[ f_L: \text{side friction factor, and} \]
\[ i: \text{superelevation}. \]

For the calculation of design standards of minimum horizontal radius, any variables are set to some values. The adopted value of side friction factor is almost corresponding to the snowy or icy road surface (around 0.2). The adopted value of vehicle speed is set to design speed. And the adopted value of superelevation is 6.0 \%.

The dimension of minimum radius of crest vertical curves is determined by the dimension of minimum stopping sight distance. The dimension value of minimum stopping sight distance is given by the equation (2).
where, $D$: stopping sight distance [m],
$v$: vehicle speed [m/s],
$\tau$: response time [s],
$g$: gravity acceleration [m/s$^2$], and
$f$: longitudinal friction factor.

In case of minimum sight distance, the adopted value of the longitudinal friction factor is corresponding to the wet road surface (around 0.4), which is about twice as that of the snowy or icy surface, and the adopted value of the vehicle speed is determined as the rage between 100% and 85% of design speed dependent on the design speed. Incidentally, the adopted value of the response time is set to 2.5 seconds, which is composed of two part; recognition time (1.5 seconds) and reaction time of brake pedal (1.0 seconds).

The fact that the road surface friction conditions for minimum horizontal radius and stopping sight distance are not consistent, and that the adopted speed values for these two conditions are also not consistent, shows the policy of geometric design in Japan does not have uniform design policy of the safety factors. Therefore the authors insist that the standards of highway geometric design must be re-examined and should be established as a uniform design policy.

3. REVERSE CALCULATIONS OF SPEED IN THE ACTUAL HIGHWAY GEOMETRY CONDITIONS

3.1 Concept

As a case study of the effects of design elements on speed potential provided by highway geometric design, the horizontal radius is chosen in this chapter. As a conceptual equation, the equation (1) can be rewritten as the equation (3) with a side friction factor as a parameter.

{the minimum horizontal radius} = Function{ design speed, superelevation}  (3)

On the contrary, if an actual value of a horizontal radius and a actual value of the superelevation at that horizontal curve are given, something like 'design speed' for the curvature can be calculated by the equation bellow with a side friction factor as a parameter.

{the reversely calculated speed} = Function{ horizontal radius, superelevation} (4)

3.2 Derivation of the 'Reversely Calculated Speed'

The 'side friction factor' adopted in the road geometry ordinance in Japan is not constant, but will change depending on vehicle speed. Though the friction factors for each design speed are given as a table in the text, the authors derived the linear relationship between vehicle speed and side friction factor referring to the table.

$f_{L}(v) = 0.16 - 0.0018 \times v$  

Substituting the equation (5) to the equation (1), and converting the vehicle speed $v$ in meters per seconds [m/s] into $V$ in kilometers per hour [km/h], the next relationship is derived with the value of 9.8 [m/s$^2$] for the gravity acceleration.
The Figure 2 shows the relationship between horizontal radius and reversely calculated speed with the value of 0.06 of the superelevation $i$.

The equation is:

$$V = -0.03175R + \sqrt{0.001R^2 + 127R(i + 0.16)}$$

(6)

3.3 Characteristics of the 'Reversely Calculated Speed'

Using the relationship shown in Figure 2, given a value of the horizontal radius actually constructed somewhere, the corresponding reversely calculated speed is derived as if something designated value for maximum safe driving speed. But the speed value shown in Figure 2 is merely something designated value because the value of side friction factor is given by the equation (5), and this relationship indicates not only physical limit of safe driving but also includes something like a safety factor policy.

For example, in case of dry surface condition, the friction factor is about four times as much as that shown in the equation (5), therefore, a vehicle driven on dry surface can go through a curve about twice as fast as that on the surface considered in the highway geometric design policy. This calculation is derived in consideration with the relation between speed and friction factor in the equation (1); the friction factor is almost proportion to the squared speed.

3.4 Case Study

Figure 3 shows the actual road geometry and calculated speed derived by the equation (6) as a case study. The specification data of road geometry such as radius of curvature and superelevation was provided by Japan Highway Public Corporation (JH). The digital data of changing points along the roadway (express as 'kp[km]', kilometers' point) and a particular value of the design element at that point is available, therefore continuous values of these design elements can be drawn in the diagram by using the knowledge about the feature of those design elements. The figure also shows the design speed of this sample section on Tomei-Expressway. The design speed is 80 [km/h] up to about 79 kilometers point, and from...
that point the design speed increases to 100 [km/h].

The figure shows the reversely calculated speeds about from 65 to 75 [kp] are relatively small because of low design speed, at the same time, within the same section, the reversely calculated speeds often exceeds more than 250 [km/h]. This fact might become one of the factors to be inconsistency of highway geometric design for safety driving.

**Figure 3. Constructed Road Geometry Specification and Reversely Calculated Speed (Tomei-Expressway, from Tokyo to Nagoya, Japan)**

4. **OBSERVATION OF ACTUAL OPERATING SPEEDS**

In general, it is very difficult to define the 'actual operating vehicle speed' as a free speed mainly because of the complexity of the observation. On the National Expressways in Japan, all maintained by Japan Highway Corporation (at the time of 2004), there are many vehicle detectors and the observed data are preserved in their data server. The format of the preserved data is every 5-minutes volume and 5-minutes average speed for each lane. The data in some section are stocked more than 10 years, or several years and so on. To utilize this enormous database, the stochastic analysis can be executed on the observations of mean speed with a volume of only one vehicle, even only one passenger car in the median lane. In this case, the mean speed can be assumed to be the speed of the one passenger car which runs absolutely independent without any other vehicle running at the same five-minute interval.
Table 1. Data Specification

<table>
<thead>
<tr>
<th>Route Name and Section</th>
<th>Length of the Route</th>
<th>Number of Detectors Installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomei-Expressway, from Tokyo to Mikkabi</td>
<td>approx. 260 km</td>
<td>144</td>
</tr>
<tr>
<td>Chuo-Expressway, from Takaido to Komaki</td>
<td>approx. 350 km</td>
<td>123</td>
</tr>
<tr>
<td>Tohoku-Expressway, from Urawa to Aomori</td>
<td>approx. 680 km</td>
<td>99</td>
</tr>
</tbody>
</table>

Figure 4. Detectors Density on Three Major Expressways
Table 2. Highway Geometric Condition of the Observation Points

<table>
<thead>
<tr>
<th>vertical</th>
<th>horizontal tangent</th>
<th>right curve</th>
<th>left curve</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>circular clothoid</td>
<td>circular</td>
<td>clothoid</td>
<td></td>
</tr>
<tr>
<td>no grade change</td>
<td>downhill</td>
<td>7</td>
<td>11</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>level</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>uphill</td>
<td>3</td>
<td>11</td>
<td>18</td>
</tr>
<tr>
<td>crest</td>
<td></td>
<td>12</td>
<td>29</td>
<td>28</td>
</tr>
<tr>
<td>sag</td>
<td></td>
<td>2</td>
<td>35</td>
<td>28</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>24</td>
<td>86</td>
<td>91</td>
</tr>
</tbody>
</table>

Figure 5. Example of Collected Frequency of Speed (Tomei-Expressway)

4.1 Data Source

The route and section analyzed in this study are listed in Table 1. The total of 366 detector location points is investigated. Figure 4 shows the detectors density for every 10 [km] in the three routes. Table 2 shows the number of observation locations classified with highway geometric conditions.

4.2 Data Error Cleansing

Figure 5 shows examples of the frequency distributions of sample speed data collected by detectors in every 5-minute interval with only one passenger car in the median lane in two years, the years 2000 and 2001.
The reason why the speed values observed are same for all detectors is caused by the time resolution of the data derived by vehicle detectors with discrete value of 20 milliseconds and speed measuring length is constant of 7 meters. For example, if a vehicle passes 7 meters with 0.2 seconds (10 times of 20 milliseconds), the speed is 126 [km/h], and 114.5 [km/h] with 0.22 seconds (11 times) and 105 [km/h] with 0.24 seconds (12 times).

The speed distributions in Figure 5 show some differences between detectors. The reason of such speed differences is considered to be mainly caused by the differences of highway geometric conditions.

On the contrary, the reason of the speed distribution for a detector position is mainly considered to be the differences of drivers’ characteristics. But is also includes the differences of driving environments (daytime or nighttime etc.), the differences of road surface conditions (dry, wet, etc.), or the differences caused by any types of accidents. The authors developed several rules to eliminate the extraordinary outstanding data as errors caused by mechanical or electric errors, traffic jam, lane blockages, etc.

4.3 Data Cleansing Based on the Concept of Different Driving Environments

Because of any environmental differences, the observed speed distributions shown in Figure 5, as an example, might be biased significantly. For examination of the effect of the road geometry on the operating speed observed, such bias factors should be omitted. To examine such bias factors, speed distributions of daytime and nighttime or those of dry and wet surface conditions are compared statistically.

For estimating road surface condition, the weather data provided by Japan Weather Association are utilized. The weather data, so called 'AMEDAS', consist of amount of rainfall in millimeters within every one hour at fixed observation stations located almost every 17 square kilometers. The source of the observed rainfall provided by AMEDAS is real observation of rainfall, therefore the reliability of the observation is very high. On the contrary, the observation station is not distributed densely, and time resolution is not so fine (only one hour volume of rainfall). In this study, the rainfall record at nearest weather observation station to a detector location is assumed to be a weather condition at the detector location.

Figure 6 shows the result of the statistic test of significant difference between dry surface condition (without any rainfall record) and wet surface condition (more than or equal to one millimeter rainfall). This figure also shows the result of the statistic test of significant difference between daytime and nighttime conditions. The statistic variable $z$ shown in the figure is defined as below.

\[
z = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}}, \quad z_{0.025} = 1.96 \quad (\alpha = 0.05)
\]

where, \(\bar{X}_1, \bar{X}_2\): sample means for group 1 and 2,
\(S_1^2, S_2^2\): sample variances for group 1 and 2,
\(n_1, n_2\): sample sizes for group 1 and 2.
From the figure, the occurrence of rainfall significantly affects on the vehicle speed, on the contrary, there is no significant difference between daytime and nighttime conditions. Therefore, in this study below, the speed data in daytime and nighttime are mixed and treated with no distinction, but all of the speed data with any rainfall record of more than or equal to one millimeter are deleted. Table 3 shows the data in analysis in chapter 5. The total number is about 500 thousand which is extracted from the total of about 77 million (= (288 data per day in one lane at one location) × (365 day per year) × (2 years) × (366 locations)).

Table 3 Data under consideration with Composition of Road Geometry

<table>
<thead>
<tr>
<th>vertical</th>
<th>horizontal</th>
<th>tangent</th>
<th>right curve</th>
<th>left curve</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>no grade</td>
<td>change</td>
<td></td>
<td>circular</td>
<td>clothoid</td>
<td></td>
</tr>
<tr>
<td>downhill</td>
<td>8,778</td>
<td>15,480</td>
<td>18,914</td>
<td>12,068</td>
<td>7,079</td>
</tr>
<tr>
<td>level</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>98</td>
</tr>
<tr>
<td>uphill</td>
<td>3,392</td>
<td>26,380</td>
<td>14,460</td>
<td>16,021</td>
<td>20,202</td>
</tr>
<tr>
<td>crest</td>
<td>11,444</td>
<td>60,224</td>
<td>33,877</td>
<td>32,257</td>
<td>38,176</td>
</tr>
<tr>
<td>sag</td>
<td>462</td>
<td>54,695</td>
<td>46,630</td>
<td>89,778</td>
<td>43,366</td>
</tr>
<tr>
<td>total</td>
<td>24,076</td>
<td>156,779</td>
<td>113,881</td>
<td>150,124</td>
<td>108,921</td>
</tr>
</tbody>
</table>

Figure 6. Statistics of the Statistic Test of Significant Differences
5. ANALYSIS OF ACTUAL OPERATING SPEEDS

Figure 7 shows the relationship between curvature of horizontal radius at the point of detector location and the average speed of the observed speed with only one passenger car within 5 minutes without any rainfall. The figure shows the tendency of inverse correlation slightly between these two variables. This fact can be expected by the equation (1), because the curvature of radius is a reciprocal of radius and radius is almost in proportion to the squared speed.

Figure 7 also shows much speed difference although the curvature value is almost same. For example, at the 0.001 [1/m] curvature (= radius of 1,000 [m]), the operating speeds cover 105 to 128 [km/h]. The vertical grade should be very critical reason for such speed differences. Possible other factors for these differences might be sequence of horizontal and vertical alignments around the detector location. For example, if severe curvature exists at the horizontal curve upstream of a detector, drivers must reduce speed within this section, so the speed observed by the detector might be slower than the case when a straight section exists upstream of the detector location.
Figure 8 shows the relationship between vertical grade and actual operating speed. Typically, in case of large value of uphill grade, the operating speeds decreased in comparison with other vertical grade conditions. The figure also shows much speed difference although the grade value is almost same. For example, at the +2 [%] grades, the operating speeds cover 95 to 120 [km/h]. It might be caused mainly by horizontal curvature.

Though the effects of the curvature of horizontal radius and the vertical grade are obvious, the effects are not linearly but have something non-linear features. Therefore, the Linear Multiple Regression Analysis cannot work so well. The authors are now trying to apply something non-linear analysis measures.

On the other hand, the authors are trying to examine the effects of the road geometries of upstream or downstream section and are trying to develop a model to explain the driving behavior of simultaneous speed change caused by highway geometric conditions.

6. CONCLUDING REMARKS

This paper shows our scheme of the study to evaluating actual highway geometric design. It includes the operating speed consistency with the proposed 'speed potential' referred to the geometric conditions. The concept of 'reversely calculated speed' is introduced and this speed can be one of the best indices to explain the 'speed potential' referred to geometric conditions. The horizontal radius at any point is approximately in proportion to the square of reversely calculated speed. In the future, the 'reversely calculated speed' should be modified to represent not only highway geometric conditions but also the safety factor.

The analysis or observation of the actual operating speed (free speed) was very difficult study because it was very difficult to observe or define those traffic conditions. In this study, utilizing enormous database observed by vehicle detectors, the operating speed is derived from the speed data with the traffic volume of only one passenger car within five-minute interval in the median lane.

To avoid the effects of wet surface on highways, the fix point weather observation data are utilized for selecting data only in the dry surface conditions. Though the mean operating speeds in daytime and nighttime have no significant difference each other, those on wet surface and on dry surface are found to be clearly different. Moreover, the operation speed on wet surface is found to be significantly slower than that on dry surface.

The operating speeds on dry surface are found to be affected by curvature of horizontal radius in case of high curvature, and also be affected by vertical grade in case of steep uphill. But the effects of those geometric design elements are not linear. The development of integrated estimation model of the operational speed with independent variables of road geometry is left in the future. The authors are now trying to develop a driver behavior model to explain the driving behavior of simultaneous speed change caused by highway geometric conditions.

ACKNOWLEDGEMENTS

The authors extend their special thanks for support in terms of providing a database with vital traffic volume and speed data to the Japan Highway Public Corporation, and for support in
terms of providing a database with rainfall data (AMEDAS) to the Japan Weather Association. The authors remark special thanks to grateful support by Associate Professor H. Oneyama, Research Associate S. Shikata and Research Associate K. Takami, in Tokyo Metropolitan University, Japan.

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