

REVIEW OF INTERNATIONAL DESIGN SPEED PRACTICES IN ROADWAY GEOMETRIC DESIGN

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INTRODUCTION

Use of the classical design speed concept as a criterion for alignment consistency on rural highways originated in the United States in the 1930's in response to increasing accident rates at horizontal curves. This concept was developed as a mechanism for designing rural highway alignments that permitted the majority of drivers to operate uniformly at their desired speed. However, as design practice and driver behavior have evolved, the concept has lost effectiveness at producing consistent alignments.

The basis of the design speed concept is the selection and application of an assumed design speed to which geometric design elements are related with the intention to ensure alignment consistency. In turn, alignment consistency can be measured with respect to the uniformity of operating speeds along the alignment.

The 1994 AASHTO Design Policy (1), the U.S. guidelines for the design of highway alignments, defines design speed as: "the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern." AASHTO gives further qualitative clarification of this rather abstract definition. However, quantitative guidance is not provided as to the percentile value in the speed distribution that should be used as the design speed. Thus, compliance is to some extent subjective and, therefore, difficult to ensure.

On the contrary the Australian rural road design guide and those of most European countries consider design speed as: "the 85th percentile of the observed free speed distribution on the longer straights (independent tangents) or large radius curves, on road sections at low traffic volumes" (2).

Researchers in the United States, Australia, and some European countries have observed disparities between design and operating speed on rural two-lane highway alignments. These studies have revealed that the 85th percentile speeds on most rural highways exceeded design speeds on curves with design speeds less than 90-100 km/h, and 85th percentile speeds were lower than design speeds on curves with design speeds greater than about 100 km/h (3,4,5).

Furthermore, as depicted in Table 1, even at the same design speed there are differences in values for minimum radius, maximum superelevation, and other design parameters, as recommended by design guidelines in different countries. Even if there was consistency with the definition and use of

design speed criterion, there are inconsistencies in the relationships between design speed and geometric design elements. These inconsistencies among design, operating speed, and geometric design have given rise to research studies aimed at finding alternative approaches to horizontal curve design.

The objective of this paper is to assess how design speed is being used in the United States and other countries internationally. Both a review of current design policies and a survey of transportation professionals from 18 countries were used to develop the evaluation.

COMMENTS ON COMMON DESIGN SPEED PRACTICES

There are several differences in the design speed concept as applied to the design of rural highway alignment in the United States and other countries. Whereas the United States and Canada continue to adhere to the design speed concept as classically applied, Australia and five other European countries, i.e., Germany, Switzerland, Great Britain, France, and Sweden, have enhanced their use of design speed to incorporate explicit consideration of actual driver speed behavior in terms of 85th percentile operating speeds. Superelevation design is also based on estimated 85th percentile speeds if they exceed the design speed of the roadway.

Below is a brief discussion of design speed practices in different countries.

United States

U.S. policy for the design of rural highway alignments is stated in the 1994 AASHTO Design Policy (1). This policy gives a quantitatively vague definition for design speed (defined above), and the concept presented does not provide sufficient coordination among individual geometric features to ensure consistency. It controls only minimum values for design speed and encourages the use of above minimum values. Recent empirical data suggest that AASHTO's recommended minimum design speeds underestimate present drivers' desired speeds (3,5). For instance, the selection of design speed as low as 48 km/h (30 mph) on rural collector highways is permitted in the AASHTO guideline on minimum design speeds.

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TABLE 1 Comparison of Some Design Parameters vs. Design Speed (100 km/h) for Different Countries

Design Parameter	United States	South Africa	Canada	Australia
Maximum Superelevation	0.08	0.10	0.08	0.10
Minimum Radius (m)	370	350	380	360
Maximum Grade	6%	6%	6%	10 - 12 %
Critical Length of Max. Grade	Reduction in Speed \leq 15 mph	200 m	Reduction in Speed \leq 15 km/h	?
Maximum Safe Side Friction Factor	0.16	0.13	0.13	0.12

The policy on superelevation design, as applied in the classical design speed concept, may contribute to operating speed inconsistencies. Policies on maximum superelevation rates and its distribution lead to superelevation rates on curves with a given radius that vary from state to state and within state from roadway to roadway depending on the state's maximum superelevation rate and the roadway's design speed (2,6). These variations in superelevation rates influence drivers' speed selection task on horizontal curves and may increase the disparity between design and operating speeds.

Because AASHTO policy assumes that drivers operate uniformly at the selected design speed, the rural alignment design process lacks a feedback loop in which the driver speed behavior resulting from the designed alignment is estimated and compared with the assumed design speed. Due to the resulting disparity between design and operating speeds, especially on low design-speed alignments, there is a need to check for and resolve disparities between design speed on individual curves and between the operating speeds on successive alignment features (7). There also exists a need to understand the influence of geometric features other than horizontal alignment on operating speed. Geometric elements in the vertical alignment, cross section, and roadside environment should all be investigated for significance in affecting operating speeds.

Several countries have adopted some or all of the AASHTO Design Policy. Therefore, countries such as Canada implement the design speed concept in essentially the same way as the United States (9).

Germany

The German design guidelines use both design and 85th percentile operating speeds for alignment design of rural

roadways. The design speed is used, as in the United States, to determine minimum radii of horizontal curves, maximum grades, and minimum k-values for crest vertical curves. The estimated 85th percentile speed, however, is used to evaluate and design superelevation rates and stopping sight distances.

The 85th percentile speed is estimated from empirical relationships based on the curvature change rate and the pavement width. The expected 85th percentile speed should

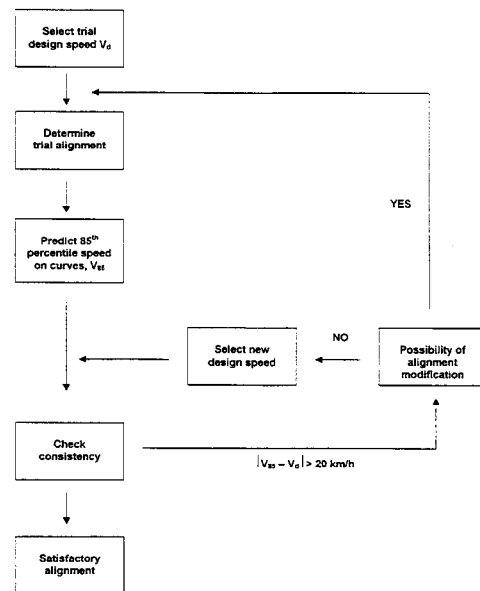


FIGURE 1 Flow Chart for the German Alignment Design Consistency Evaluation

not exceed the design speed by more than 20 km/h; otherwise, the guidelines require that either the design speed be increased or the design be modified to reduce the expected 85th percentile speed. Thus, the design process

involves a feedback loop in which the driver speed behavior resulting from the designed alignment is estimated and compared with the assumed design speed.

The flow chart presented in Figure 1 illustrates the German alignment design procedure.

Switzerland

The Swiss alignment consistency procedure (8) estimates the speed profile along an alignment and identifies excessive speed differentials between successive elements. The speed profile is estimated based on the speed on horizontal curves, maximum speed on tangents, and the deceleration and acceleration rates entering and exiting horizontal curves.

The Swiss speed profiles were originally supposed to represent the observed 85th percentile speeds, but recent data showed increased speeds on sharper curves with its corresponding increase in accident experience. Instead of some modifications, the Swiss retained the original speed-radius relationships, and it is used as a design tool for safe speed on sharper curves.

Great Britain

Current British standards (2) emphasize that sections of two-lane rural highways should have either clearly adequate or clearly inadequate passing-sight distance and that sections with marginally adequate passing-sight distance should be avoided in alignment design. The standards permit curves with large enough radii to provide adequate passing-sight distance, or curves with radii small enough that passing-sight distance is clearly inadequate, and, thus, will not be misjudged by drivers when adequate road signs are provided.

However, curves with intermediate radii that drivers might incorrectly judge as having adequate passing-sight distance are not recommended. Unlike the United States and most of Europe, the British do not employ functional classification concepts. Instead, they emphasize the effects of alignment and layout (cross-section and access control) constraints on operating speeds in selecting a design speed.

The alignment constraint is a function of "bendiness" which is defined as the total degree of curvature per kilometer and the harmonic mean of available sight distance (2). The layout constraint is a function of the road type (two-lane and multi-lane divided), cross-section width, and access density. This approach attempts to balance design and operating speeds to achieve cost and environmental savings by using an iterative procedure for the selection of design speed and the geometric alignment design.

Australia

The current Australian roadway design standards (Austroads, 1989) presents revised design procedures for low-speed alignments that incorporate consideration of operating speeds in order to improve alignment consistency. For roadways with lower design-speeds, there is greater variation in operating speed. For low-speed (i.e., ≤ 90 km/h) alignments, the predicted 85th percentile speed is used as the design speed (4).

For high design-speed (i.e., ≥ 100 km/h) alignments, the classical design speed concept is still in use, because for such alignments, studies revealed that the 85th percentile speeds were less than the design speed. A series of tables and figures is used to estimate the operating speed along the alignment. An alignment is divided into sections, and the operating speed is estimated for each of these sections. Realizing the drivers will increase their speeds on tangent sections, the Australia design guidelines give the expected increase in speed on the tangent sections, corrections are included for sections with positive grades. A designer can begin at one end of the corridor with the section speed and continue along the alignment and determine the operating speed at any point along the corridor. The process also allows for checks on the minimum curve radii for curves based on the entering speed into a curve. For example, a curve may have an appropriate curve radius for the selected design speed, but if the curve is preceded by a long tangent then the operating speed may increase well above the design speed. This curve radius may not be appropriate for the actual operating speeds for vehicles entering this curve.

EVALUATION OF ALIGNMENT CONSISTENCY

The principal operating-speed-based measure of alignment consistency is the change in the 85th percentile operating speed from an approach tangent to a horizontal curve. The Swiss (8) use speed profiles to maintain alignment consistency. The speed profile for a roadway should satisfy the following conditions:

1. If the preceding element is a tangent or large-radius curve, i.e., ≥ 420 m, then the speed differential to the succeeding curve should be ≤ 5 km/h. This measure was implemented because more problems have been observed at curves following a long tangent than at curves following a sequence of curves.
2. The operating speed differential for a sequence of curves should be ≤ 10 km/h.
3. The existing sight distance should equal or exceed the length of transition required to change speed at a rate of 0.8 m/sec^2 between successive curves.

If any of the above three conditions is violated, accident

involves a feedback loop in which the driver speed behavior resulting from the designed alignment is estimated and compared with the assumed design speed.

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If any of the above three conditions is violated, accident

experience on the roadway is checked. If there is an accident problem, action is taken to correct the inconsistency.

Leisch and Leisch (1977) and Lamm et al. (1988) developed operating-speed-based rural alignment consistency evaluation procedures in the United States. However, these procedures have not been widely used.

The procedure of Leisch and Leisch is based on the following rules:

1. Average automobile speeds along an alignment should vary by no more than 16 km/h (10 mph).
2. Design-speed reductions between consecutive sections should not exceed 16 km/h (10 mph).
3. Average truck speeds should differ from average automobile speeds by no more than 16 km/h (10 mph).

Lamm et al. (1988) ranked horizontal alignment consistency based on the change in degree of curvature (ΔD) and the corresponding change in 85th percentile operating speeds (ΔV_{85}) between successive horizontal elements, as follows:

1. $\Delta D \leq 5^\circ$ or $\Delta V_{85} \leq 9.7$ km/h (6 mph) \rightarrow good design.
2. $5^\circ < \Delta D \leq 10^\circ$ or 9.7 km/h $< \Delta V_{85} \leq 19.3$ km/h (12 mph) \rightarrow fair design.
3. $\Delta D > 10^\circ$ or $\Delta V_{85} > 19.3$ km/h (12 mph) \rightarrow poor design.

SURVEY OF DESIGN SPEED PRACTICES

A survey of design speed practices was sent to 30 individuals representing 23 countries. Responses were received from 22 individuals from 18 countries, resulting in a response rate of approximately 75 percent. The following is a list of the countries responding:

- Australia
- Canada
- China
- Denmark
- England
- France
- Germany
- Greece
- Japan
- Netherlands
- Norway
- Poland
- Portugal
- South Africa
- Sweden
- Switzerland
- Venezuela
- Yugoslavia

The survey questions concentrated on the definition and application of design speed. Inquiries were made on how design speed procedures differ between high-speed and low-speed facilities and what is the relationship among design speed, actual operating speed, and speed limit. The survey also probed the research needs related to design speed.

Definition and Selection of Design Speed

All of the countries reported using design speed as a significant criterion in the design of streets and highways. There were three commonly mentioned principles found in the definitions of design speed. Design speed represents:

1. the maximum or highest speed a motorist can travel
2. the speed at which the motorist is safe or comfortable
3. the speed resulting from the influence of geometric features

While most of the countries responded that design speed is set for favorable weather conditions; two countries, England and the Netherlands, responded that design speed is a measure of the speed under wet pavement conditions.

There was some variation in the influential factors for selecting design speed. The most frequently mentioned factors are listed in Table 2 (multiple responses were allowed). Over 60 percent of respondents said design speed was a function of topography. Another factor frequently mentioned as used in determining design speed were road function and road type. Traffic volume, cost considerations, and the type of environment (either rural, suburban, or urban) were also mentioned by several countries.

TABLE 2 Factors Influencing Selection of Design Speed

Factor	Number Responding
Topography	14
Road function	13
Road Type	10
Traffic (volume and quality)	6
Cost/Economy	5
Environment (rural/urban)	5

Operating Speed Models

Although design speed should represent the maximum safe speed at which a driver will negotiate a section of roadway under favorable conditions, the actual operating speeds can differ significantly from the design speed. This problem was noted by several respondents.

In attempts to resolve the differences between operating speed and design speed, several countries have developed an operating speed or speed profile approach to help in applying the design speed criterion. Australia, England,

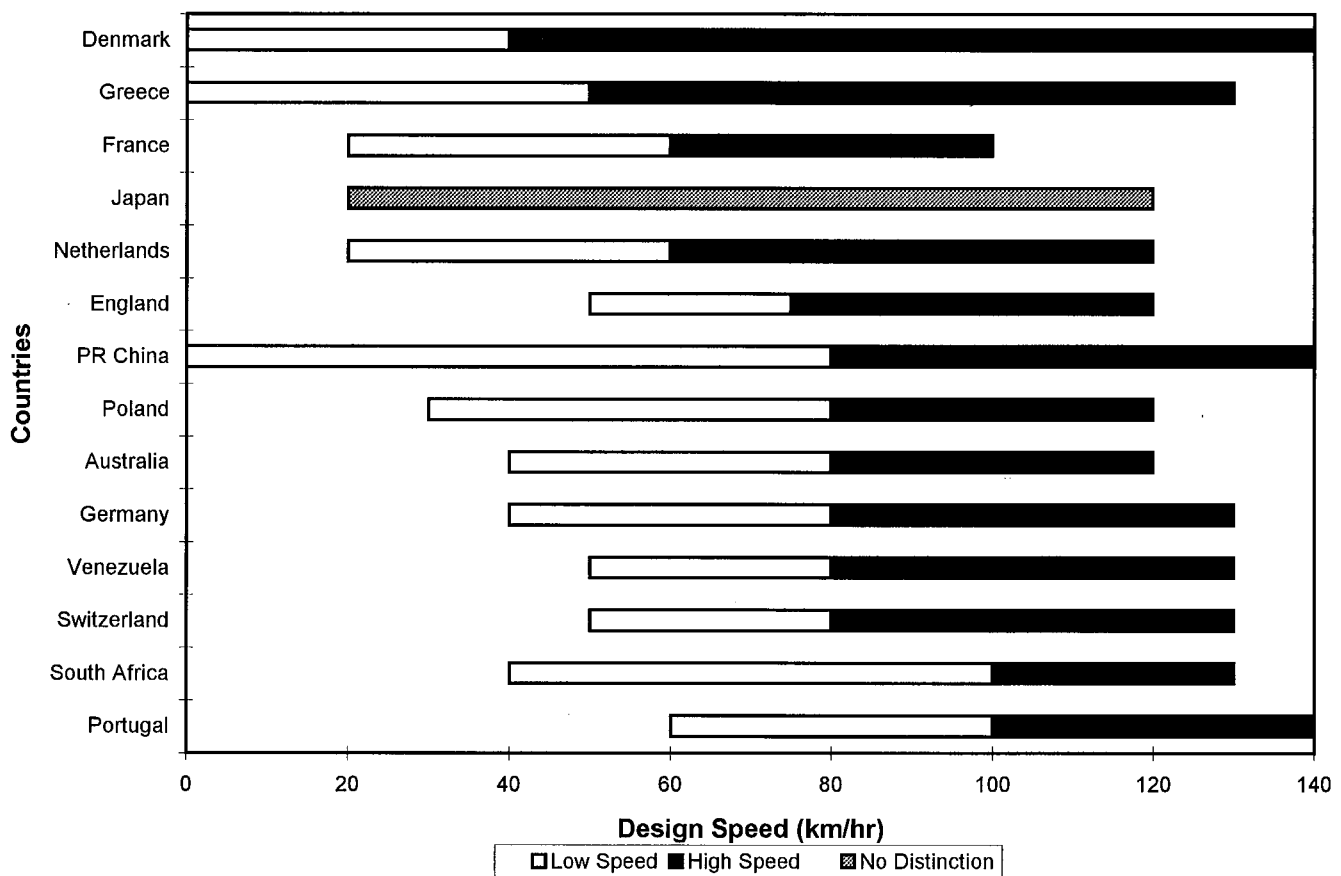


FIGURE 2 Design Speed Ranges

France, Germany, Poland, Switzerland, and Yugoslavia also indicated their guidelines incorporate an operating speed procedure (four of these countries have been highlighted earlier in this paper). The premise behind estimating the operating speed is to give the designer feedback on the operation of the preliminary design or alignment. If the operating speed exceeds the design speed by more than a specified amount, adjustments must be made to the design of the alignment, roadway classification, or design speed.

One aspect of the operating speed approach not discussed in the responses was a confidence measure for the estimate of the 85th percentile speed. The operating speed approach estimates the 85th percentile speed along sections of roadway, but there is still significant variation in operating speed between similar sections of roadway. The designer needs guidance on how many kilometers per hour the actual 85th percentile speed may differ from the estimated 85th percentile speed. Another way of approaching the confidence measure would be to show that there is 95 percent confidence that 80 to 90 percent of the drivers will be driving below the estimated 85th percentile operating speed.

High-Speed and Low-Speed Design

Most of the responses indicated that there were ranges of design speeds provided in the national design policies and manuals. In many countries, these design speed ranges were provided for both high-speed and low-speed design. The variation of design speed ranges is presented in Figure 2. The application of the design speed procedure for the different speed ranges generally did not differ for the countries. Approximately one-third of the respondents, however, did identify that their country's low-speed design procedures deviated from high-speed design procedures.

The AASHTO Design Policy separates procedures for high-speed (>80 km/h) and low-speed design (<60 km/h) (1). For example, the minimum curve radius for a given design speed is smaller in low-speed design due to the assumption for side friction factors. The higher side friction factor in low-speed design is based on the fact that drivers will accept greater lateral acceleration in negotiating horizontal curves in low-speed urban environments. Nearly one-third of the respondents stated that there was a difference in procedures for low-speed design. Some countries presented similar evidence of

higher side friction factors for low-speed design in their design policy. Other countries said their design policy did not present the design speed criteria for low-speeds. In these instances, designers are left to their own discretion concerning the design speed and corresponding operating speed of the facility.

Responses from Australia, Greece, and Venezuela indicated there are not established design speeds for low-speed urban streets. The designer is expected to use judgement on the operating speed (sometimes by examining similar facilities) and set the design speed based on the expected operating speed. The 85th percentile speed should generally be used as the minimum design speed. The Australian design guide suggests using a design speed of 10 km/h to 20 km/h above the 85th percentile speed.

Responses from Portugal and England indicated that for low-speed environments there are exceptions to the minimum design values provided in the design policy. Venezuela indicated that for very low speeds they do not use the design speed, but they give some guidelines for some geometric design elements (grade, superelevation, and lane width).

The Swedish design policy presents a *safety priority design speed* that has almost the opposite objective as design speed. It uses a "maximum" design value for alignment elements instead of a "minimum" alignment element design values. The aim is a design that limits the maximum possible spot speed and provides a smooth low-speed profile. Traffic calming techniques such as short segment lengths, narrow cross-sections, deflections, small radius roundabout, bumps, narrow cross sections, short sight distances, and low alignment standards are used to accomplish this operation.

Relationship Among Design Speed, Operating Speed, and Posted Speed Limit

Many survey responses commented on the discrepancies between design speed and the actual observed speeds or 85th percentile speeds. In general, the operating speeds are below the design speed on many high-speed facilities. In these cases, one design speed can be used for substantial sections of roadway, resulting in operating speeds below the design speed. There are fewer geometric features that directly influence speed for high-speed facilities. Curve radius, available sight distance, and vertical alignment (grade and type of terrain) are the primary geometric features related to design speed. Though some countries identified cross section as a function of design speed, many cross sectional elements are selected to provide the maximum safety in high-speed

environments and do not greatly influence speeds.

The problem of operating speeds exceeding the design speed is more prevalent on low-speed roadways. This may reflect that in the absence of restrictive horizontal alignment less is known about the relationships between operating speed and other geometric features. Designers have little to no information on how elements such as lane width, land use, lateral obstructions, and access density affect operating speeds. Some countries indicated that design speed should be 10 km/h to 20 km/h higher than the expected 85th percentile speed. In the low-speed environment, this increase in design speed may actually create a design that looks more aligned with high-speed operation, resulting in greater operating speed variation.

In China, it is assumed that for high-speed facilities, operating speed is 60 to 70 percent of the design speed. For low-speed facilities, operating speed is assumed to be 80 to 90 percent of the design speed. A couple of responses indicated that in off-peak hours vehicle operating speed should be equal to or lower than design speed; during peak-hours, the operating speed should be significantly lower than the design speed. Japan indicated the assumed relationship in 1970 was operating speeds were approximately 20 km/h below design speed at high-speeds and operating speeds and design speed nearly equal at low-speeds. The respondent conveyed concern that operating speeds have increased, and thus, changed this relationship in the 1990s.

Other countries suggested the speed relationship resulted in 85th percentile speeds higher than design speed. Portugal showed operating speed to be higher than design speed by 20 km/h at intermediate speeds and equal at higher speeds. Greece indicated, for rural roads, the 85th percentile speed is equal to design speed plus 20 km/h for high-speed roadways and design speed plus 30 km/h for low-speed roadways. There were also some responses that indicated that there are more important influences on speed such as traffic volume and speed limits.

Over a third of the responses indicated that design speed was used in the determination of posted speed limit. This results in many countries because the posted speed limit is determined based on the functional classification of the roadway at the same step design speed in selected. Other countries suggested that because the design speed is related to the 85th percentile speed, the design speed should represent the posted speed limit.

Design Speed Issues and Research Needs

Respondents were also asked to identify other issues or research needs pertaining to design speed. The following

shortcomings in the design speed process were noted:

- driver speed (actual operating speed) does not always correspond to design speed
- design speed does not ensure design consistency along an alignment
- design speed is too general a term in its current use
- design speed is not cost effective when rigidly applied
- the design speed procedure is insufficient for low-speed design

In response to some of the deficiencies in the design speed process, the following research needs were identified:

- greater determination of the relationship between design speed and operating speed
- investigation of the relationship between design speed and cross sectional elements
- development of safety criteria for designs speed and operating speed consistency
- investigation of advisory speed signing for horizontal curves following tangent sections
- implications of snow and ice to design speed

Summary of Surveys

There appear to be two general methods of applying the design speed criterion. Many countries use a similar approach to the AASHTO design policy in the United States. This policy provides a method for selecting a theoretical design speed as the maximum safe speed determined by geometric alignment under favorable conditions. However, there is no practical method for relating the design speed concept to the actual operating speeds experienced on a street or highway. The second approach incorporates an operating speed model or speed estimation procedure. The operating speed approach gives the designer a method to check if the anticipated operating speed agrees with the originally selected design speed. If the design speed and operating speeds are not in agreement, evaluation can be made of modifications to the alignment design. While this later approach appears to provide significant benefits in evaluating design consistency, the process has not been applied as widespread in the low-speed environment.

CONCLUSIONS AND RECOMMENDATIONS

It can be concluded from recent studies and the papers submitted for this conference that horizontal curves whose design speeds are less than drivers' desired speed on adjacent independent tangents exhibit operating speed inconsistencies. This results in an increased accident potential on horizontal curves. Also, the U.S. rural

alignment design policy as presented in the AASHTO, unlike similar guidelines in Australia and some European countries, such as Germany and Switzerland, lacks the ability to identify and address operating-speed inconsistencies.

As in several European countries and Australia, it is pertinent that a balanced design policy for rural two-lane highways incorporates a feedback loop to estimate 85th percentile speeds on horizontal alignments. This is to check for large disparities between design and 85th percentile speeds on a particular curve and between the 85th speeds of successive horizontal alignment elements. Modification of the alignment design to reduce the disparities should be carried out when necessary. This idea was also recommended by Lamm et al., Voigt and Krammes, and Cardoso.

AASHTO should review recent data on the distribution of present day drivers' desired speeds on rural highways, and consider revisions to its recommended minimum design speeds that represent, quoting from the AASHTO, "a high-percentile value in this speed distribution." The exact percentile should be further investigated. Though the international practice is to use the 85th percentile, a higher percentile might be considered especially for low-speed two-lane rural roads.

Further research should be undertaken to fully develop and validate the speed-profile procedures for evaluating alignment consistencies to be included in design guidelines. Also, rules or standards for consistency of successive elements, for a well-balanced relation design and curvilinear alignments and limits of minimum length of tangents based on estimates of expected operating speeds should be established to reflect current drivers' behavior.

Operating speed and relation design backgrounds like those presented by Lamm et al. should be part of every modern highway design guideline when aiming for a good curvilinear alignment which is consistent and exhibits higher levels of safety.

REFERENCES

1. A Policy on the Geometric Design of Highways and Streets. American Association of State Highway and Transportation Officials, Washington, DC, 1994.
2. Federal Highway Administration Research Report. "Highway Alignment Design Consistency for Rural Two-lane Highways." FHWA-D-94-034, January 1995.
3. Chowdhury, M.A. Warren, D.L., and H. Bissell, "Analysis of Advisory Speed Setting Criteria." Public Roads, Vol. 55, No. 3. December 1991, pp.65-71.

4. McLean, J.R., "Speeds, Friction Factors, and Alignment Design Standards." Research Report ARR 154. Victoria, Australia: Australian Road Research Board, 1988.
5. Messer, C.J., Mounce, J.M., and R.Q. Brackett, "Highways Geometric Design Consistency Related to Driver Expectancy, Vol. III, Methodology for Evaluating Geometric Design Consistency." Report No. FHWA/RD-81/037. Washington, D.C., Federal Highway Administration, 1981.
6. Hayward, J.C., "Highway Alignment and Superelevation: Some Design Speed Misconceptions." Transportation Research Record 757, 1980, pp. 22-25.
7. Lamm, R., Steffen, H., and A.K. Guenther, "Procedures for Detecting Errors in Alinement Design and Consequences for Safer Redesign. TRR, 1445. Cross Section and Alinement Design Issues, 1994.
8. Swiss Norm 640 080b. Vereinigung Schweizerischer Strassenfachleute, Zurich, Switzerland, 1992.
9. Geometric Design Standards for Canadian Roads and Streets. Roads and Transportation Association of Canada, Ottawa. 1979.