A PRACTICAL SAFETY APPROACH TO HIGHWAY GEOMETRIC DESIGN INTERNATIONAL CASE STUDIES: GERMANY, GREECE, LEBANON, AND THE UNITED STATES

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ABSTRACT

A practical procedure, which considers safety rules and criteria for the safety evaluation of new designs, redesigns, and RRR-projects, is presented in this paper. The procedure is based on statistical investigations of speeds and design parameters in Europe, the Middle East, and North America. The main components of the procedure are:

- Operating speed backgrounds,
- Relation design backgrounds,
- Skid-resistance backgrounds, and
- Driving dynamic backgrounds,

for tangents, curves, and transitions to curves, for different roadway types and topography classes.

The procedure presented in this paper provides interrelationships between design parameters, driving behavior, and driving dynamics, in order to determine sound roadway alignments and/or to detect poor ones, and to positively influence the accident situation.

INTRODUCTION

Generally speaking, any evaluation of road safety, such as in the driving dynamic field, has been conducted more or less qualitatively. It is safe to say, from a traffic safety point of view, that no one is able to say with great certainty, or prove by measure or number, where traffic accidents could occur or where accident black spots could develop (*1*).

However, everyone agrees that there exists a relationship between traffic safety and geometric design consistency. By all means, alignment consistency represents a key issue in modern highway geometric design. A consistent alignment would allow most drivers to operate safely at their desired speed along the entire alignment. However, existing design speed-based alignment policies permit the selection of a design speed that is less than the desired speeds of a majority of the drivers (*2-6*).

Previous research on rural two-lane highway operations and safety has concluded that horizontal curves whose design speed is less than drivers' desired speed exhibit operating-speed inconsistencies that increase accident potential (*7, 8*). Accident research has consistently found that accident rates on horizontal curves are 2 to 5 times the accident rates on tangent sections of rural two-lane highways (*9, 10*).

Bearing this in mind, a practical procedure, which considers safety rules and criteria for the safety evaluation of new designs, redesigns, and restoration, rehabilitation or resurfacing (RRR) projects, is presented in this paper. The procedure is based on statistical investigations of speeds and design parameters in Europe, the Middle East, and North America (*11-14*). The main components of the procedure are:

- Operating speed backgrounds,
- Relation design backgrounds,
- Skid-resistance backgrounds, and
- Driving dynamic backgrounds,

for tangents, curves, and transitions to curves, for different roadway types and topography classes.

The procedure presented in this paper provides interrelationships between design parameters, driving behavior and driving dynamics, in order to determine sound roadway alignments and/or to detect poor ones, and to positively influence the accident situation. The procedure encompasses traffic volumes of up to 12,000 vehicles per day and longitudinal grades of up to 6 percent; that means between 80 to 90% of the two-lane rural road network of the countries under study is covered.

BACKGROUND

Figure 1a schematically shows the fatality distributions for different road categories in selected countries. On the basis of this figure, it can be estimated that more than 50% of the fatalities can be attributed to accidents that occur on two-lane roads outside built-up areas, and at least half of them can be attributed to those that occur on curved roadway sections.

These estimations are supported by the results of Brinkman and Smith (*15*), who reported that horizontal curves are ranked with intersections as the most likely locations for accident concentration on two-lane rural highways.

Thus, curved sites represent one of the most important critical locations for answering the question, "where do people die", and for considering measures to reduce accident frequency and severity. For this reason, two-lane rural safety is considered to be one issue of pressing national concern in both Europe and the United States.

Multilane highways, on the other hand, are much safer.

For example, the U.S. Interstate system and the comparable German Autobahn system, with about 10% of the total number of fatalities, represent the safest road class (Figure 1a), even though 25% of the vehicle kilometers driven are normally done on these roads. Thus, multilane highways are normally designed very generously. That means that curvilinear aspects are more or less included in the design of those roads (*16*).

Figure 1b schematically shows the distribution of fatalities by age in selected countries. As can be seen from the figure, young drivers between the ages of 15 and 24 years are the most endangered, due primarily to excessive speed and lack of driving experience. This age group accounts, on average, for about 28% of all highway fatalities in both Europe and the United States, even though it represents about 16% of the populations of both continents. This implies that the percentage share of fatalities for this age group is roughly twice the figure that this age group makes up of the total population. In order to avoid misunderstandings, note that the larger fatality portion of the age group 25 to 64 years in Figure 1b is related to a period of 40 years, whereas the age group 15 to 24 years only encompasses 10 years.

Note also that the percentage share of fatalities for the age group over 64 is much higher than the percentage figure that this age group makes up of the total population (Figure 1b). Therefore, with respect to the question, "who dies", it can be concluded that the age groups "15 to 24" and "over 64" are the most endangered age groups.

Even though significant improvements in traffic safety have been reached in the last decades, the positive development has been different on urban roads, on two-lane rural roads, and on Interstates (Autobahn) (*17*).

For instance, the number of fatalities in built-up areas (urban) in West Germany experienced a 75% decrease between 1970 and 1990. During the same time period, fatalities in nonbuilt-up areas (rural, without Interstates) experienced a 50% decrease. Since the end of the 1970's, the fatality rate on two-lane rural roads has been constantly higher than that on urban roads. A similar development has been experienced by a number of European countries and states of the United States.

The previous statements proved, first of all, that two-lane rural roads experience the highest accident risks and severities. Therefore, this portion of the road network should be regarded especially when designing, redesigning, and conducting RRR projects.

The safe and efficient movement of traffic is greatly influenced by the geometric features of the highway. A review of accident spot maps normally shows that accidents tend to cluster on curves, particularly on very sharp curves. Even though the design engineer possesses detailed information - derived from driving dynamic formulas and standard values - on driving through a curve, accident frequency and severity often do not appear to coincide with the actual driving behavior. Many of these speed errors may be related to inconsistencies in horizontal alignment that cause the driver to be surprised by sudden changes in the road's characteristic, to exceed the critical speed of a curve and to lose control of the vehicle. These inconsistencies can and should be controlled by the engineer, when a roadway section is designed or improved.

To evaluate quantitatively horizontal alignments in the future, three safety criteria were developed (see Table 1) (*3, 12, 13, 16, 18, 19*) in order to achieve:

- design consistency (Safety Criterion I),
- operating speed consistency (Safety Criterion II), and
- driving dynamic consistency (Safety Criterion III).

The development of the first two safety criteria shown in Table 1 is based on:

- the experience of Safety Criterion I that, when considering individual design elements (curves or tangents) along the observed roadway section, the absolute difference between the 85th-percentile speed and the selected design speed should correspond to certain ranges.
- the experience of Safety Criterion II, that the driving behavior of motorists expressed by the absolute difference of the 85th-percentile speeds between successive design elements (tangent to curve or curve to curve) should also fall into certain ranges, in order to differentiate between good, fair, and poor design practices.

The 85th-percentile speed is defined as that speed below which 85% of vehicles operate under free flow conditions, on clean, wet road surfaces.

The safety criteria presented in Table 1 express the need to alleviate the accident risk and severity at curve sites and the corresponding transitions. In this connection, it was found that the most successful parameter in explaining much of the variability in 85th-percentile speeds (V_{85}) and accident rates (AR) on two-lane rural roads is the design parameter "curvature change rate of the single circular curve with transition curves (CCR_s)". This parameter describes the design of a curve through the length-related course of the curvature, which appears to be one of the most important variables regarding both the operating speed and the accident situation. Furthermore, this new design parameter includes the influence of the transition curves (in front of and behind the circular curve), and regards the overall length and the deflection angle at the curved sites (*13, 19*).

CCR_s is calculated from the following formula:

$$CCR_s = \frac{\left(\frac{L_{cr}}{R} + \frac{L_{cl1}}{2R} + \frac{L_{cl2}}{2R}\right) * 63700}{L} \qquad (1a)$$

where:

$L = L_{cr} + L_{cl1} + L_{cl2}$ = Length of Curve [km]
CCR_s = Curvature Change Rate of the Single Circular Curve with Transition Curves [gon/km]
L_{cr} = Length of circular curve [m]
R = Radius of circular curve [m]
L_{cl1}, L_{cl2} = Length of clothoids in front and behind [m].

Without regarding transition curves, the formula reads:

$$CCR_s = 63700/R \qquad (1b)$$

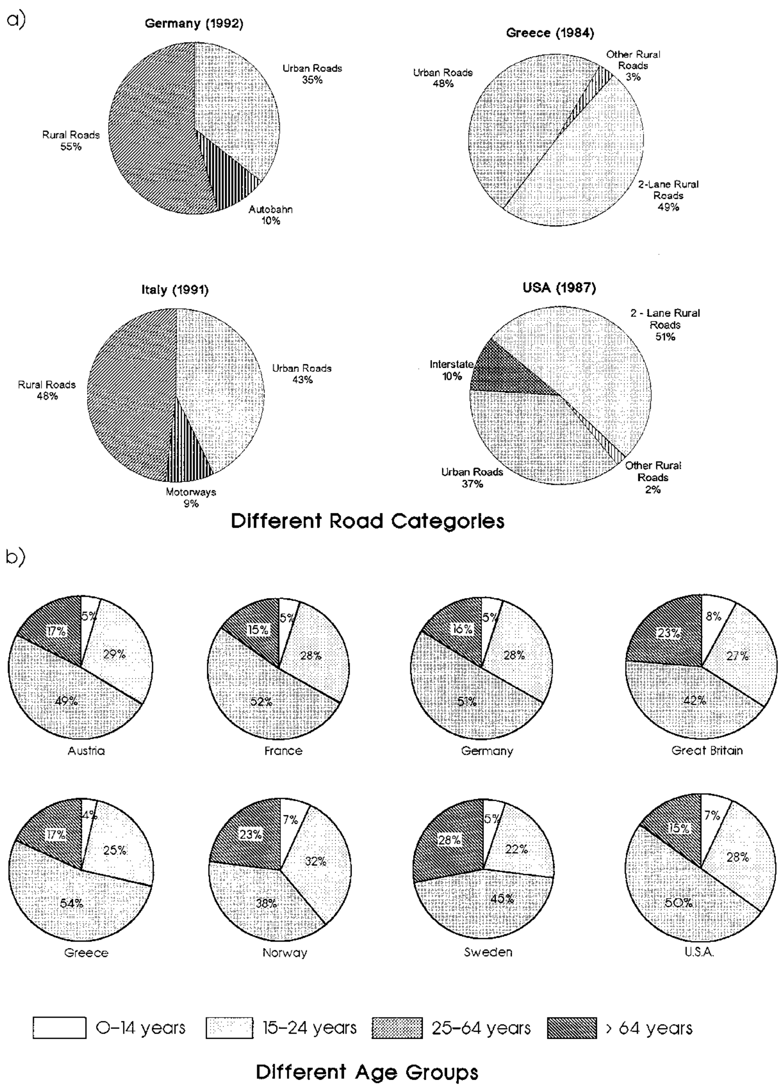
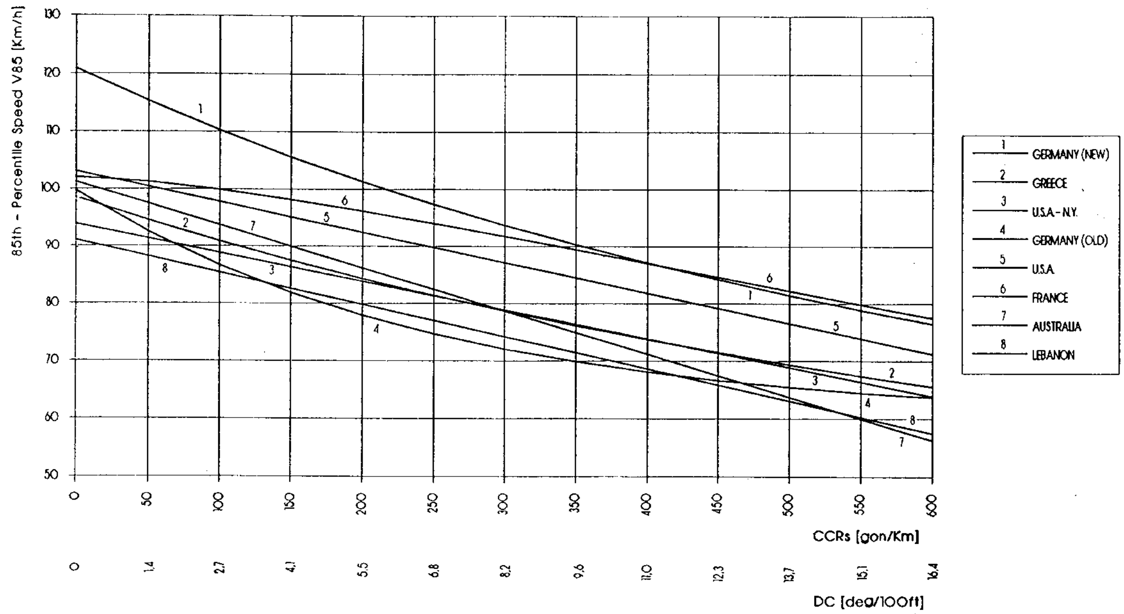


FIGURE 1 Distribution of Fatalities for Selected Countries



Legend: For curve-numbers and additional information, see Table 2.

FIGURE 2 Operating Speed Background for Two-lane Rural Roads in Different Countries (All Lane Widths)

The mathematical relationship between the American design parameter "Degree of Curve (DC)" and the newly developed design parameter "CCR_s" for circular curves without transition curves is as follows:

DC_{ft} [Degree/100 ft] x 36.5 CCR_s [gon/km] (2)

36.5 [-] = conversion factor DC_{ft} (Imperial System) to CCR_s (Metric System) without regarding transition curves.

OPERATING SPEED BACKGROUNDS

In order to determine operating speeds, expressed herein by the 85th-percentile speeds, with respect to the curvature change rate of the single circular curve with transition curves (CCR_s), the so far known and new operating speed backgrounds for a number of countries were compiled in Figure 2. Corresponding equations (Equations 3-10) are given in Table 2.

By knowing DC- or the CCR_s-values for the curved roadway sections and/or independent tangents ($CCR_s = 0$), the 85th-percentile speeds can be determined from Figure 2 for the respective country under study. Existing or planned horizontal alignments can then be characterized according to the ranges of Safety Criteria I and II in Table 1 as good, fair, or poor design levels.

Operating speed backgrounds (like those in Figure 2) should be part of every modern highway design guideline when striving for a good curvilinear alignment, and for a more consistent and safer road characteristic. In this way, design consistency (Safety Criterion I) and operating speed consistency (Safety Criterion II) can be achieved through the good design level according to Table 1. Minor inconsistencies correspond to the fair design level, whereas major design inconsistencies correspond to the poor design level.

RELATION DESIGN BACKGROUNDS

"Relation design" means no more single design elements with minimum or maximum limiting values are put together more or less arbitrarily, but rather design element sequences are formed, in which the design elements following one another are subject to specific relations or relation ranges (*16*).

In order to achieve operating speed consistency between two circular curves in the same or in the opposite directions, at least for two-lane rural roads, the radii of these curves shall be in a well-balanced relationship (known as relation design). The same is true for the transition independent tangent to curve; certainly with respect to the accident situation this is the more crucial case.

This requirement coincides with the assumptions of Safety Criterion II that, for good design practices, for example, the range of change in operating speeds between successive design elements should not exceed 10 km/h (Table 1). In other words this indicates a well balanced design or a good curvilinear alignment. The same is true for fair design, where the range of change in operating speeds should not exceed 20 km/h. This indicates a fairly balanced design or a tolerable curvilinear alignment. However, with respect to poor design practices according to Safety Criterion II, a change of more than 20 km/h in operating speeds would certainly indicate an unbalanced design, or a critical alignment.

Therefore, the ranges of change in operating speeds according to Safety Criterion II were taken as the basis for calculating relation design backgrounds, based on the respective operating speed background of the country under study (Figure 2 or Table 2). How the relation design diagrams were developed (see Figure 3) is alluded to in the following for Germany, as an example.

According to Table 2, the regression model for the operating speed background of Germany corresponds to:

$$V_{85} = 10^6/(8270 + 8.01 \times CCR_s) \qquad (3)$$

Step 1: Set R = 1000 m.

Step 2: Calculate CCR_s with respect to R from Equation (1) without regarding transition curves.

==> $CCR_s = 63700/R$

==> $CCR_s = 63700/1000 = 63.7$ gon/km.

Step 3: Determine V_{85} from Equation (3)

==> $V_{85} = 114$ km/h.

TABLE 1 Ranges for the Safety Criteria I to III for Good, Fair, and Poor Design Levels

Safety Criterion	GOOD Permissible Differences	FAIR (Tolerated Differences)	POOR (Non-Permissible Differences)
	Design Levels		
I 1)	$\lvert V_{85i} - V_d \rvert \leq 10$ km/h	10 km/h $<$ $\lvert V_{85i} - V_d \rvert \leq 20$ km/h	20 km/h $<$ $\lvert V_{85i} - V_d \rvert$
II 2)	$\lvert V_{85i} - V_{85i+1} \rvert \leq 10$ km/h	10 km/h $<$ $\lvert V_{85i} - V_{85i+1} \rvert \leq 20$ km/h	20 km/h $<$ $\lvert V_{85i} - V_{85i+1} \rvert$
III 3)	$+0{,}01 \leq f_R - f_{RA}$	$-0{,}04 \leq f_R - f_{RA} < +0{,}01$	$f_R - f_{RA} < -0{,}04$

Legend:

1) Related to the individual design element "i" (independent tangent or curve) in the course of the observed roadway section.

2) Related to two successive design elements "i" and "i+1" (independent tangent* to curve or curve to curve).

3) Related to one individual curved roadway section.

V_d = design speed [km/h]

V_{85i} = expected 85th-percentile speed of design element "i" [km/h],

V_{85i+1} = expected 85th-percentile speed of design element "i+1" [km/h], (according to Figure 2),

f_R = side friction "assumed" [-],

f_{RA} = side friction "demanded" [-],(according to Equations 13-15)

* An "Independent Tangent" is classified as being long enough to be regarded in the "curve-tangent-curve" design process as an independent design element, whereas a short tangent is called "non-independent" and can be neglected (*20*).

TABLE 2 Regression Models for Operating Speed Backgrounds

Two-Lane Rural Roads:

1. Germany, New [14]
   $V_{85} = 10^6/(8270 + 8.01 \times CCR_S)$ $R^2 = 0.73$ (3)
   Speed Limit: 100 km/h

2. Greece [12]
   $V_{85} = 10^6/(10150.1 + 8.529 \times CCR_S)$ $R^2 = 0.81$ (4)
   Speed Limit: 90 km/h

3. U.S.A. [21]
   $V_{85} = 93.85 - 1.82 \times DC = 93.85 - 0.05 \times CCR_S$ $R^2 = 0.79$ (5)
   Speed Limit: 90 km/h

4. Germany, Old [22]
   $V_{85} = 60 + 39.70 \times e^{(-3.98 \times 10^{-3} \times CCR_S)}$ (6)
   Lane width: 3.50 m, Speed Limit: 100 km/h

5. U.S.A. [23]
   $V_{85} = 103.04 - 1.94 \times DC = 103.04 - 0.053 \times CCR_S$ $R^2 = 0.80$ (7)
   Speed Limit: 90 km/h

6. France [24]
   $V_{85} = 102/[1 + 346/(63700/CCR_S)^{1.5}]$ (8)
   Speed Limit: 90 km/h

7. Australia [25]*
   $V_{85} = 101.2 - 2.73 \times DC = 101.2 - 0.075 \times CCR_S$ $R^2 = 0.87$ (9)
   Speed Limit: 90 km/h

8. Lebanon [26]
   $V_{85} = 91.03 - 2.06 \times DC = 91.03 - 0.056 \times CCR_S$ $R^2 = 0.81$ (10)
   Speed Limit: 90 km/h

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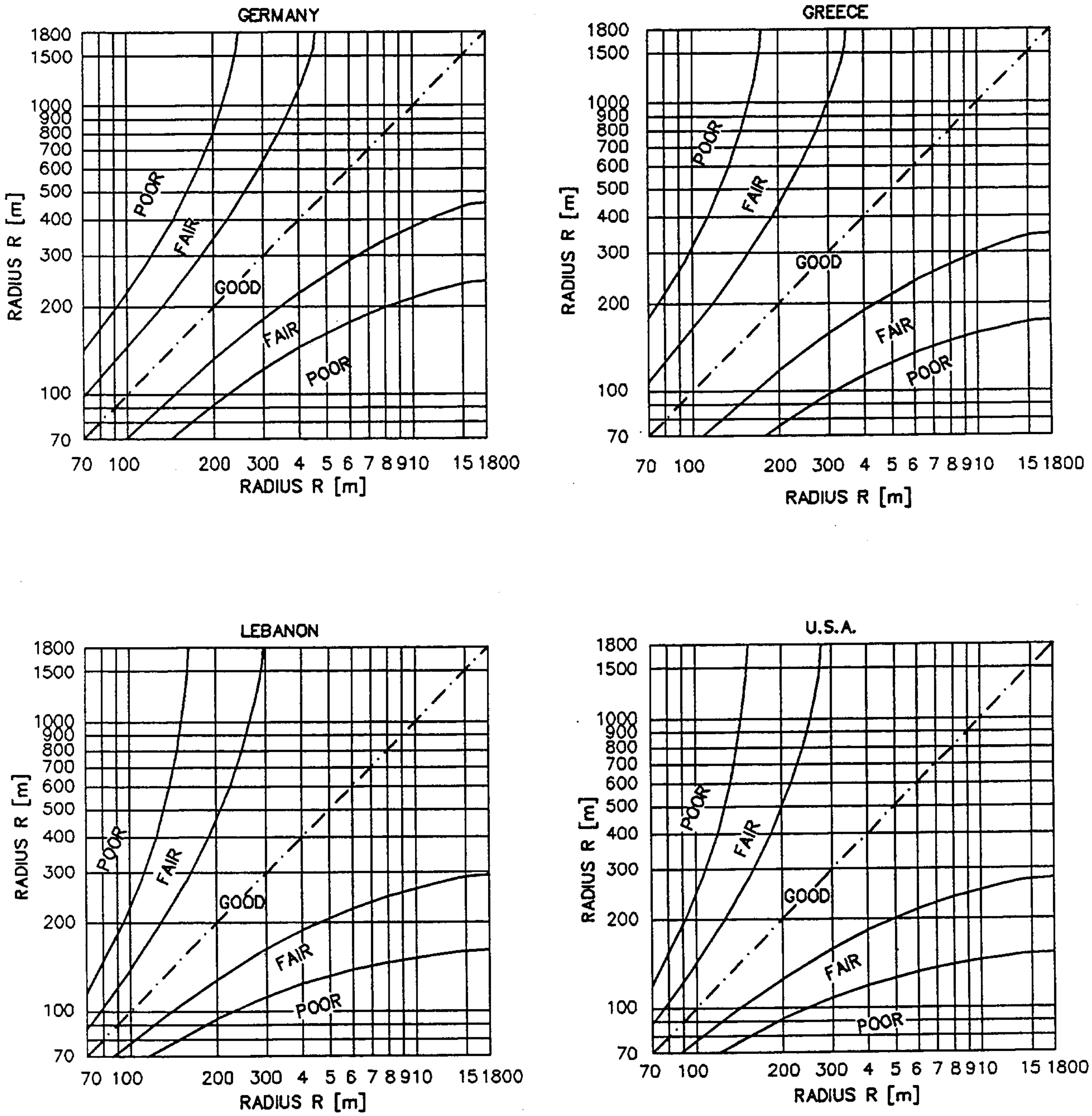
*Meanwhile from McLean a new regression model for Australia was provided, which is so far not incorporated into Figure 2:

$V_{85} = 101.2 - 1.56 \times DC = 101.2 - 0.043 \times CCR_s$ (9 NEW) (3)



New Development:
Safety Research has revealed, that relation designs in the fair range for radii of curve of R≤ 200 m should be avoided and those for R≤ 350 m should be used only in exceptional cases. Therefore, it will be considered in the future to limit the fair range to V_{85i} - V_{85i+1}≤ 15 km/h.

FIGURE 3: Relation Design Backgrounds for Two-Lane Rural Roads for Selected Countries

Step 4: Subtract 10 km/h from V_{85} in Step 3 to reflect good design or 20 km/h to reflect fair design (see Table 1)

==> V_{85} = 104 km/h for good design

V_{85} = 94 km/h for fair design

Step 5: For V_{85} in Step 4, determine CCR_s from Equation (3) and R from Equation (1b).

For good design

CCR_s = 169 gon/km

or R = 377 m,

and for fair design

CCR_s = 297 gon/km

or R = 215 m.

Step 6: The intersections of the lines drawn horizontally or vertically from curve radii of 1000 m and 377 m, and from 1000 m and 215 m, respectively, indicate the points which should fall on the relation design curves for good and fair designs.

Step 7: Repeat Steps 1 through 6 for radii of curve of less than and greater than 1000 m with increments of 100 m.

Using this procedure, the relation design backgrounds for Germany, Greece, Lebanon, and the United States were developed. From the relation design curves the designer in the country under study could immediately decide whether certain radii of succeeding curves fall into the ranges of good, fair, or poor design. For instance, from the relation design background of the United States a radius of curve of 500 m, combined with a radius of curve of

R = 100 m means "Poor Design"

R = 180 m means "Fair Design"

R = 300 m means "Good Design"

R = 1500 m means "Good Design", also.

New designs of two-lane rural roads should always be assigned to the "good design level" (Table 1).

Redesigns and RRR-strategies also can be assigned in substantiated individual cases to the fair design level. However, note that, based on the experiences gained (*1, 3, 21*), the expected accident rate is at least twice as high as that for "good design". Also a higher accident cost rate may result. In this connection new research has revealed that relation designs in the fair range for radii of curve of R 200 m should be avoided) (see also Figure 3).

In cases of speed differences in the range of "poor design", a new design has to be considered for existing roadway sections. If not, an unfavorable alignment with respect to the actual driving behavior can be expected from safety and economic points of view, because of the normally high accident risk and the resulting high accident costs.

For the transition independent tangent - (clothoid)-circular curve, the "good design" range must apply. That means, according to Figure 3, that curve radii (R) of at least

- Germany: 500 m (calculated)
- Greece : 400 m (calculated)
- Lebanon: 300 m (calculated)
- U.S.A. : 300 m (calculated)

must follow independent tangents (*20*).

Similar conclusions were established in several other studies. For instance, Krebs and Kloeckner (*32*) indicated in a study conducted in 1977, which was based on a large database of traffic accidents in Germany, that curve radii of 400 to 500 m provide a certain cross-point in safety on circular curves and in the corresponding transition sections (*1*). This result was later confirmed by Lamm et al. in a study conducted in the United States and in Germany in 1989 (*33*). Another 1989 study conducted by Leutzbach and Zoellmer (*34*) compared the transitions between tangents and circular curves, with and without transition curves (clothoids), in Germany. They indicated the following: "With respect to the element sequence for the transition from tangents to curves a safety gain by the inclusion of a transition curve (clothoid) could only be observed for curve radii less than 200 m, where accident rates were significantly lower in comparison to the direct sequence 'tangent-circular curve'. No systematic differences were detected for curve radii R > 200 m a finding which also applied to the accident cost rate for the entire range of investigated curve radii".

Based on the above findings and research results, it can be expected that the introduction of a minimum radius of curve of 400 to 500 m for the transition "tangent - transition curve - circular curve" will not affect the accident situation negatively, so far as the selected design speed does not require larger curve radii.

However, to stay on the safe side, for the direct transition between independent tangents and circular curves without transition curves the above values were doubled. That means curve radii between 800 m and 1000 m could follow independent tangents directly without an additional transition curve.

Of course, one should not forget the importance of other design impacts that transition curves provide, besides accident-related issues, such as

- gradual increase or decrease of the centrifugal force
- convenient desirable arrangement for superelevation run-off
- improvement of the optical appearance.

Thus, for achieving gentle curvilinear alignments as well as sound transition between independent tangents and curves in cases of new designs, major reconstruction, and RRR-projects, the highway engineer should examine horizontal alignments by

- Safety Criterion I according to Table 1,
- Safety Criterion II according to Table 1, and
- The Relation Design Ranges according to Figure 3.

If all three evaluation procedures fall into the good design range, it can be said definitely that a sound alignment exists. Normally, the results of Criterion II and the design ranges in Figure 3 correspond to each other, since both evaluation procedures depend on similar assumptions. The results of Safety Criterion I, however, must to be regarded as fully independent.

In the same way, existing two-lane rural roads can also be classified for detecting fair and poor design practices in order to evaluate endangered (fair) and dangerous (poor) road sections.

SKID RESISTANCE BACKGROUNDS

Figure 4 shows the so far known skid resistance backgrounds (*27*). The 90th or the 95th-percentile distribution curves in these skid resistance backgrounds are usually used to determine the maximum permissible tangential friction factors (f_{Tperm}), such as in Germany (*22*). Note that skid resistance backgrounds, like those in Figure 4, do not exist so far for all countries. An overall regression relationship (called: "Overall Regression Curve") between tangential friction factor and design speed was established (*27*), based on the assumptions for maximum allowable tangential friction factors in the Federal Republic of Germany, France, Sweden, Switzerland, and the United States (see Figure 5). The developed overall regression curve and the corresponding Equation (11) were later compared with actual skid-resistance inventories in Germany and the United States (see Figure 4). This figure shows that the overall regression curve covers between 80 and 90% of the skid resistance values in Germany and about 90% in New York State. Therefore Equation (11) is considered to be reasonable for safety, economic, and environmental demands and is recommended for determining stopping sight distances and radii of crest vertical curves in modern highway geometric design tasks (*12*).

$$f_{Tperm} = 0.59 - 4.85 \times 10^{-3} \times V_d + 1.51 \times 10^{-5} (V_d)^2 \quad (11)$$

f_{Tperm} = maximum permissible tangential friction factor [-]
V_d = design speed [km/h].

After the establishment of the relationship between the maximum permissible tangential friction factor and the design speed, the question raised is the range from which the utilization ratio "n" of the maximum permissible side friction factor shall be selected. Based on international experiences, this value varies between n = 40% and n = 50% for rural roads. That means that there will be still 90% and 87%, respectively of friction available in the tangential direction for acceleration, deceleration, braking, or evasive maneuvers when driving through curves (*2*). Thus, the equation for the maximum permissible side friction factor is

$$f_{Rperm} = n \times 0.925 \times f_{Tperm} \quad (12).$$

The reduction factor of 0.925 corresponds to tire-specific influences.

Based on specific topographic conditions (flat, hilly and mountainous topography) different utilization ratios were considered as reasonable for side friction factors. The recommended Equations (13) and (14) for maximum permissible side friction factors (f_{Rperm}) with respect to topography are given in Figure 5 (*12, 13, 19*).

Flat Topography (n = 45 %)

$$f_{Rperm} = 0.25 - 2.04 \times 10^{-3} \times V_d + 0.63 \times 10^{-5} \times (V_d)^2 \quad (13)$$

Hilly and Mountainous Topography (n = 40 %)

$$f_{Rperm} = 0.22 - 1.79 \times 10^{-3} \times V_d + 0.56 \times 10^{-5} \times (V_d)^2 \quad (14)$$

f_{Rperm} = maximum permissible side friction factor

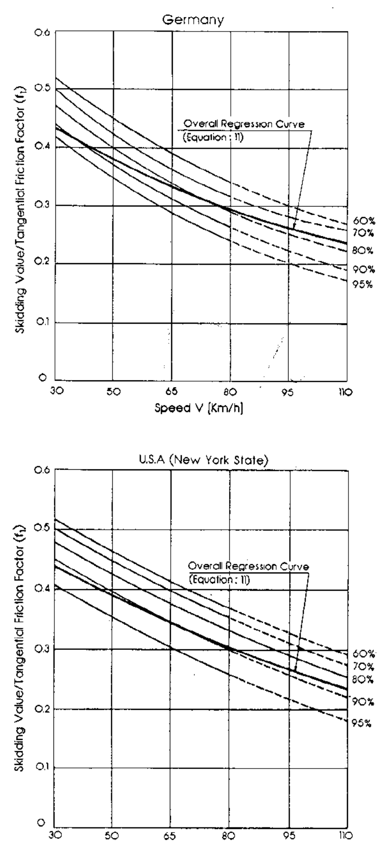


FIGURE 4 Skid Resistance Backgrounds (*27*)

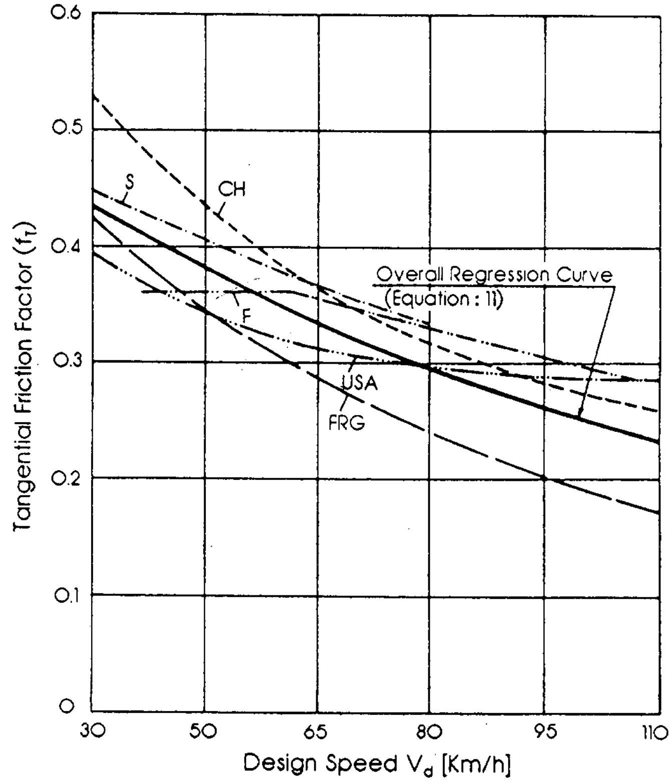


FIGURE 5 Relationship Between Maximum Permissible Tangential Friction Factor and Design Speed for Different Countries, along with the Overall Regression Curve

DRIVING DYNAMIC BACKGROUNDS

The side friction factors for curve design, assumed for different design speeds in the Geometric Design Guidelines of Germany (*22*) and the United States (*31*), are often exceeded by those demanded by the 85th-percentile speeds under real world conditions (*28-30*). These situations begin with CCR_s-values of greater than about 225 gon/km and correspond to curve radii (R) of less than about 280 m, according to Figure 6, for Germany and the United States. Furthermore, it could be shown in the case of good design levels, that the side friction assumed (f_R) exceeds side friction demand (f_{RA}). In the case of poor design levels, side friction demand exceeds side friction assumed (Figure 6).

Based on accident research by the authors (*3, 7, 9, 12, 13, 18, 19, 21, 28-30*), it could be proved, that the following differences of CCR_s-values and DC-values represent good, fair and poor design levels:

Good Design

range of change: $\Delta CCR_s \leq 180$ gon/km

$\Delta DC \leq 5°$

Fair Design

range of change: $180 < \Delta CCR_s \leq 360$ gon/km

$5° < \Delta DC \leq 10°$

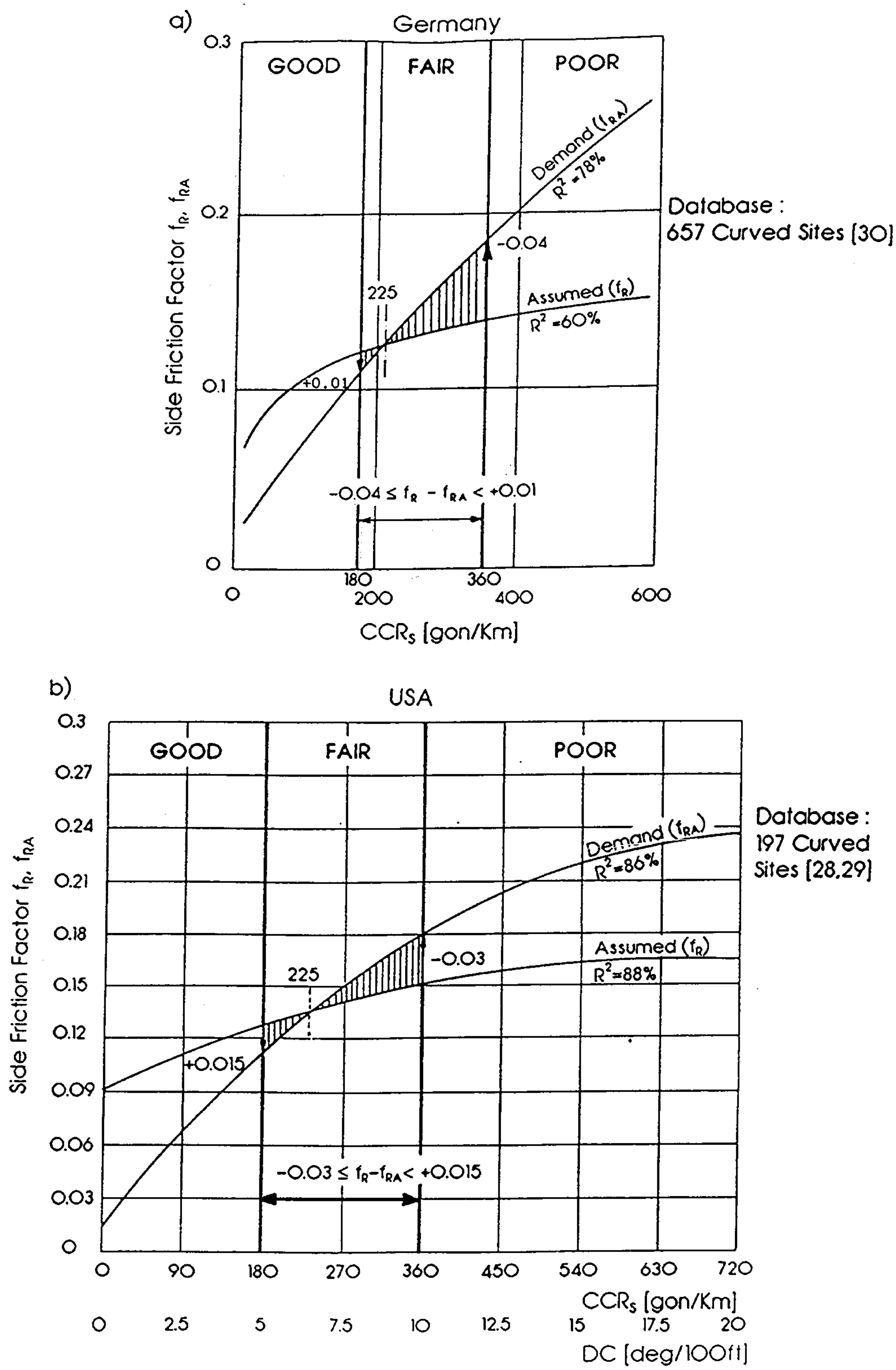
Poor Design

Range of change: $\Delta CCR_s > 360$ gon/km

$\Delta DC > 10°$.

These ranges were incorporated in the driving dynamic backgrounds of Germany and the U.S.A. in Figure 6.

As can be seen from Figure 6 the limiting values for "good" and "poor" design levels are nearly the same for Germany and the United States. It was decided, however to use the German limiting values as the permissible and non-permissible ranges for Safety Criterion III (providing adequate dynamic safety of driving through circular curves), shown in Table 1. The decision to select the German values is based on the fact that besides circular curves the influence of transition curves is regarded additionally here. For example the value of "-0.04" (Figure 6a) could mean that at the beginning of poor design already 4% of superelevation is missing.



f_R = Side Friction Assumed; f_{RA} = Side Friction Demand

FIGURE 6 Driving Dynamic Backgrounds for Side Friction Assumed/demand, Related to the Curvature Change Rate of the Single Curve

Side friction assumed (f_R) has to be determined again based on Equation (12). However, new research has revealed that the so far selected utilization ratios of n = 40% and n = 45% for providing as much driving dynamic safety as possible in respect to new designs (see Figure 5), are too conservative for a generally valid evaluation process according to Safety Criterion III. Note that the procedure should not only regard new designs, but contain also the examination of existing alignments, as well as of redesigns and RRR-strategies. Therefore, based on many case studies in different countries, it is recommended to use for the calculation of "side friction assumed (f_R)" an utilization ratio of n = 70%. That means that there will still be 76%, of friction available in the tangential direction, when driving through curves (*2*). Thus, the formula for side friction assumed (f_R) reads:

$$f_R = 0.70 \times 0.925 \times f_{Tperm} \tag{15}$$

for f_{Tperm}, see Equation (11).

Side friction assumed remains constant along the investigated roadway section.

Another problem exists regarding the design speed (V_d) with respect to the Safety Criteria I and III and to Equation (11). While for new designs the selected design speed is known, this is not true for existing alignments in respect of intended redesigns and RRR-projects. For the estimation of a sound design speed, it is recommended in those cases to calculate the average CCR_s-value based on all the curves in the observed roadway section according to Equation (1a). Tangent sections should remain unregarded. For this length-related average CCR_s-value the 85th-percentile speed (V_{85}) has to be determined from Figure 2 for the country under study. This average "V_{85}" represents a good estimate for the design speed (V_d) for future redesigns and RRR-strategies, since this speed will to a certain extent optimize the design process from the viewpoints of economic, environmental and safety-related issues.

Side friction demanded (f_{RA}) has to be determined from the following basic dynamic formula, depending on the 85th-percentile speed:

$$f_{RA} = \frac{(V_{85i})^2}{127 * R} - e \tag{16}$$

where:

V_{85i} = expected 85th-percentile speed of the investigated curved section "i" [km/h],

R = radius of curve [m],

e = superelevation rate.

By knowing side friction assumed (f_R) and side friction demand (f_{RA}) the safety evaluation process according to Safety Criterion III can be conducted, too.

CONCLUSION

The establishment of operating speed backgrounds, and relation design backgrounds, is an important assumption that must be regarded when establishing modern highway geometric design guidelines.

These statements should clarify that operating speed backgrounds like those used in Figure 2 depend significantly on the driving behavior of motorists in the specific country under study.

Consequently the relation design backgrounds for different design levels should be developed on the basis of operating speed backgrounds, as it is demonstrated in the paper. Therefore, evaluation backgrounds for achieving a sound "Relation Design" like those in Figure 3 are important assumptions for every country when establishing geometric design guidelines for highways.

For example, by applying the relation design backgrounds of Figure 3, the designer of the country under study could immediately decide whether certain radii of succeeding curves or the transitions from independent tangents to curves fall into the range of good, fair, or poor design practices.

Thus, for achieving gentle curvilinear alignments and sound transitions between independent tangents and curves in cases of new designs, major reconstructions and RRR-projects, the highway engineer should examine his horizontal alignment by

- Safety Criterion I according to Table 1,
- Safety Criterion II according to Table 1, and
- The Relation Design Ranges according to Figure 3.

If all three evaluation procedures fall into the good design range, it can be said definitely that a good and sound alignment exists. Normally, the results of Safety Criterion II and for the design ranges in Figure 3 correspond to each other, since both evaluation procedures depend on similar assumptions. The results of Criterion I, however, must be regarded as fully independent.

In the same way, existing two-lane rural roads can also be classified for detecting fair and poor design practices in order to evaluate endangered (fair) and dangerous (poor) road sections.

With respect to driving dynamic safety aspects, the development of

- Skid Resistance Backgrounds, and

• Driving Dynamic Backgrounds

is also important in order to guarantee appropriate maximum permissible tangential and side friction factors, as well as reliable ranges for Safety Criterion III.

Of course the question may arise, how practical are the discussed safety evaluation procedures. Therefore, to better illustrate their utility in design, a case study for a test road is given by Reagen, Stimpson, Lamm, Heger, Steyer and Schoch in papers at this International Symposium, entitled: "Influence of Vehicle Dynamics on Road Geometrics".

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