Safety Evaluation Process of Two-Lane Rural Roads
- A Ten Year Review -

by

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Abstract

A practical procedure, which considers explicitly the driving behavioral- and safety rules of a horizontal alignment for the evaluation of roadway new designs, redesigns, and RRR-projects is presented in this paper. Design classes were developed to classify, from a traffic safety point of view, roadway sections as good, fair or poor designs and are associated with three Safety Criteria to develop an overall quantitative safety evaluation procedure for two-lane rural roads. The safety criteria are introduced to analyze and evaluate by

Criterion I	Design consistency –relation control between design speed and actual driving behavior;
Criterion II	Operating speed consistency – uniformity control of 85th-percentile speeds through successive elements of the road; and
Criterion III	Consistency in driving dynamics – which relates side friction assumed with respect to the design speed to that demanded at the 85th-percentile speed.

Furthermore, it is dealt with the issues: design speed, operating speed, sound tangential and side friction factors, as well as the application of tangents in the design process.

A comparative analysis of the actual accident situation with the results of the Safety Criteria reveals a convincing agreement. Thus, the great advantage of the new concept is, that already in the design stages the Safety Criteria can predict the endangerment (low, medium, high) for new alignments or allow statements about the safety conditions of existing (old) roadway sections or whole road-networks.

BACKGROUND

In 1988 a new design procedure to promote design consistency in highway geometric design, as defined by operating speeds and accidents expected, was presented (1). The procedure is based on three safety criteria, which lead to an overall safety evaluation process for new and existing two-lane rural roads. Furthermore, the idea to regard the tangent as an independent design element was introduced (2). An independent tangent is classified as one that is long enough to be considered as an independent design element in the curve-tangent-curve safety evaluation design process, while a short tangent is called non-independent and can be neglected. At that time it was already recognized, at least since the seventies (3-6), that "abrupt changes in operating speed because of horizontal alignment are a leading cause of accidents on two-lane rural roads." Therefore, an objective and convenient method for locating alignment inconsistencies, which may cause abrupt operating speed changes, was requested. Such a mechanism would enable the engineering agency to provide cost-effective horizontal alignment modifications, and thereby enhance traffic safety.

What has to be considered in establishing modern highway geometric design recommendations (9) remains an exciting, thought-provoking question in the field of highway engineering. While several important goals in highway geometric design, such as function, traffic quality (capacity), economy, are reasonably well understood today, deficiencies still exist in the proper analysis and evaluation of the impact of highway geometric design on traffic safety.

Geometric design guidelines have long been the subject of dispute in the literature. Some argue that the guidelines do not present a clear measure for evaluating the safety level of roadways. Many authors have expressed concern over the lack of quantitative safety considerations in the highway geometric design guidelines of the last decades. For example it is cited:

- Unlike other engineering fields, in road design it is almost impossible to determine the safety level of a road. In other words, the guidelines provide no basic values to describe the safety level of a road in relation to design parameters and traffic conditions; whereas in other engineering fields, such as structural, there exist safety criteria for constructing, for example, bridges or buildings (7), or

- if the guidelines guarantee the safety of a road, then "no" or "only a few" accidents should occur on that road. When accidents happen, drivers are always the ones who take the blame for the mishap, or

- accidents are not uniformly distributed on the road network. High accident locations are a clear indication that, besides driver's error, there exist other influencing parameters which are characterized by the road itself (8).

The safe and efficient movement of traffic is greatly influenced by the geometric features of the highway. Accident spot maps normally show that accidents tend to cluster on curves, particularly on very sharp curves. Furthermore, it can be shown that two-lane rural roads pose the highest accident risks and severities. Therefore, this portion of the road network should be given special emphasis, and it appeared necessary to develop a practical procedure, which considers driving behavior and safety rules for the evaluation of new designs, redesigns, and Rehabilitation, Restoration, Resurfacing (RRR)-projects. Thus, for more than ten years the Institute for Highway and Railroad Engineering (ISE) of the University of Karlsruhe developed, tested and applied in practical design- and safety-related work, three quantitative safety criteria. Those criteria aim to provide rural two-lane highways with:

- design consistency,
- operating speed consistency, and
- driving dynamic consistency,

to enhance traffic safety. These criteria are the *main focus* of the traffic safety portions of the new "Highway Design and Traffic Safety Engineering Handbook" (9).

HIGHWAY SAFETY EVALUATION TERMINOLOGY, FRAMEWORK AND OVERVIEW

This paper provides criteria whereby the safety of the alignment of a section of road can be tested and the required remedial measures identified.

Consistency

It has been found that 50 to 60 percent of traffic fatalities occur on two-lane rural roads. At least half of these occur on curved roadway sections. Addressing these fatalities, three safety criteria have been developed. These are:

Criterion I	-	The difference between design speed and driving behavior as expressed by variations in observed 85th-percentile speeds.
Criterion II	-	The difference between observed 85th-percentile speeds on successive design elements.
Criterion III	-	The difference between side friction assumed for design and side friction demanded at the 85th-percentile speed level on curves.

Criterion I is a measure of the consistency of the alignment. Criterion II reflects the harmony (or disharmony) between operating speeds on successive design elements. Criterion III refers to the adequacy of the safety dynamics provided. All three criteria are evaluated in terms of three ranges, described as “Good”, “Fair” and “Poor”. Cut-off values between the three ranges are developed and are applied to both curves and tangents. In the case of tangents, their treatment differs from that of the curves (10).

Curves

The impact of the design parameters curvature change rate of the single curve, length of curve, superelevation rate, lane width, shoulder width, sight distance, grades and traffic volume between 1,000 and 12,000 veh. per day on two-lane rural highway sections was investigated in the United States, Germany, Greece and Italy. This investigation showed, that the most successful parameter in explaining much of the variability in operating speeds and accident rates was the new design parameter curvature change rate of the single curve. All the other design parameters revealed insignificance in the regression models at the 95%-level of confidence.

The simple formula for determining the curvature change rate of the single curve with transition curves is given by the following equation (9):

$$CCR_S = \frac{\left(\frac{L_{Cl1}}{2R} + \frac{L_{Cr}}{R} + \frac{L_{Cl2}}{2R}\right)}{L} \cdot \frac{200}{\pi} \cdot 10^3 = \frac{\left(\frac{L_{Cl1}}{2R} + \frac{L_{Cr}}{R} + \frac{L_{Cl2}}{2R}\right)}{L} \cdot 63{,}700 \qquad \text{(Eq. 1)}$$

where:

CCR_S = curvature change rate of the single circular curve with transition curves [gon/km],

L = $L_{Cl1} + L_{Cr} + L_{Cl2}$ = overall length of unidirectional curved section [m],

L_{Cr} = length of circular curve [m],

R = radius of circular curve [m],

L_{Cl1}, L_{Cl2} = lengths of clothoids (preceding and succeeding the circular curve), [m].

(The dimension “gon” corresponds to 400 angle units in a circle instead of 360 degrees).

Tangents

Tangents require special attention. A tangent can either be independent (long), in which case it will be regarded in the design process, or not (short), where it is simply ignored. In order to draw a distinction between long and short tangents, it is necessary to consider the operating speed, V85, that can be achieved on the tangent in relation to the operating speeds appropriate to the curves on either side of it. Three possibilities exist. These are according to Figure 1:

Case 1: The tangent length is such that it either is not, or is just, possible, in going from a shorter to a longer radius, to accelerate to the operating speed of the following curve within the length of the tangent; $TL \leq TL_{min}$ (non-independent tangent, not considered in the safety evaluation process, the sequence curve-to-curve is relevant).

Case 2: The tangent length allows acceleration up to the maximum operating speed, $V85_{Tmax}$, on tangents; $TL \geq TL_{max}$ (independent tangent, considered in the safety evaluation process, the sequence tangent-to-curve is relevant).

Case 3: The tangent length is such that it is possible to achieve an operating speed higher than that of the following curve but not as high as that achieved without the constraint of nearby curves; $TL_{min} < TL < TL_{max}$ (independent tangent, considered in the safety evaluation process, the sequence tangent-to-curve is relevant).

The calculation of the tangent lengths, TL_{min} and TL_{max}, requires calculation of the operating speed under the various circumstances. This procedure is described later on according to Eqs. 5 to 7.

Design vs. Safety

To get a better overview of the real accident situation the “Curvature Change Rate of the Single Curve” was arranged into different CCR-classes for 6 large databases, one from the U.S.A., four from Germany and one from Greece, which fundamentally all reveal similar results. The results of three of these databases are listed in Table 1 for the accident rate.

For every design/CCR_s-class a mean accident rate was calculated (Eq. 11, Table 5). The selected ranges of the CCR_s-classes from 180 to 360 gon/km and from 360 to 550 gon/km go back to the original investigations in the United States, which were related to the U.S. design parameter “degree of curve”. The conversion of the original ranges of the DC-classes (ΔDC = 5 to 10 deg./100 ft. and ΔDC = 10 to 15 deg./100 ft.) leads to the selected CCR_s-classes in Table 1.

As shown in Table 1, the t-test results indicate significant increases (at the 95%-level of confidence) in the mean accident rates between the different CCR_s-classes compared; that means, higher accident rates can be expected with higher CCR_s-classes, despite the stringent traffic warning devices often installed at curve sites (18).

The significant results of Table 1 indicate for three databases and different accident types:

1) gentle curvilinear horizontal alignments consisting of tangents or transition curves, combined with curves up to CCR_s-values of 180 gon/km (that corresponds roughly to radii of curve of greater or equal than 350 m without considering transition curves) experienced the lowest average accident risk, classified here as “good design”;
2) the accident rate on sections with CCR_s-values between 180 and 360 gon/km (that corresponds roughly to radii of curve between 175 and 350 m) was at least twice or three times as high as that on sections with CCR_s-values up to 180 gon/km, classified here as “fair (tolerable) design”;
3) the accident rate on sections with CCR_s-values between 360 and 550 gon/km (databases 1 and 2) was about four to five times higher than that on sections with CCR_s-values of up to 180 gon/km, classified here as “poor design”;
4) for CCR_s-values greater than 550 gon/km (roughly radii of curve of less than 115 m), the average accident rate was even higher.

Analysis of mean accident cost rates (Eq. 12, Table 5) demonstrated results similar to those shown in Table 1 (9, 11). Based on the presented results of accident research it can be assumed that the proposed CCR_s-ranges represent a sound classification system for the arrangement of good, fair (tolerable) and poor design practices in modern highway geometric design.

THREE QUANTITATIVE SAFETY CRITERIA FOR HIGHWAY GEOMETRIC DESIGN

Safety Criterion I

Of special interest in modern highway geometric design is ”achieving design consistency”. That means, the design speed (V_d) shall remain constant on longer roadway sections, and shall be tuned at the same time with the actual driving behavior, expressed by the 85th-percentile speed (V85) of passenger cars under free flow conditions.

This is guaranteed by the good design level of Safety Criterion I in Table 2, that means the difference between 85th-percentile speed and the design speed shall not exceed 10 km/h along the whole observed roadway section. In this way, the road characteristic is well balanced for the motorist along the course of the road section.

Safety Criterion II

The 85th-percentile speed shall be consistent along the roadway section, as well. This is guaranteed by the good design level of Safety Criterion II ”Achieving Operating Speed Consistency” between two successive design elements (either from curve to curve or from tangent to curve). Therefore the 85th-percentile speed differences between two design elements also should not exceed 10 km/h for good design practice (Table 2). Accordingly speed differences between 10 and 20 km/h correspond to fair design levels, whereas speed differences greater than 20 km/h definitely classify poor design for Safety Criteria I and II.

Safety Criterion III

A well-balanced driving dynamic sequence of individual design elements within a road section with the same design speed promotes a consistent and economic driving dynamics pattern. This is provided by Safety Criterion III ”Achieving Driving Dynamic Consistency” for the good design level in Table 2. This Safety Criterion relies heavily on sound driving dynamic assumptions for tangential and side friction factors, as will be demonstrated later on.

For the safety evaluation process, we need now sound information, how to determine

- the design speed (V_d),
- the 85th-percentile speed (V85), as well as
- side friction assumed (denoted in Table 2 as f_{RA}) and side friction demanded (denoted as f_{RD}).

Speed-Related Criteria

Safety Criteria I and II are related to speed differentials. Two speeds are of interest, being the design speed and the operating speed (Table 2).

Design Speed

Design speed has been used for several decades to determine sound alignments. However, sight should not be lost of the fact that design speed merely defines the lowest standard achieved on the road section. It is therefore possible to introduce severe inconsistencies into the design. For example, at low and intermediate design speeds, road sections of relatively flat alignment may produce operating speeds that exceed the design speed by substantial amounts (10). Furthermore, in the case of existing or old alignments, the originally selected design speed may not be known, and it is thus necessary to estimate it. This can be done by determining the average CCR_S-value across the length of the road without consideration of the intervening tangents. This average CCR_S is thus calculated as:

$$\varnothing CCR_S = \frac{\sum_{i=1}^{i=n} (CCR_{Si} \cdot L_i)}{\sum_{i=1}^{i=n} L_i} \qquad \text{(Eq. 2)}$$

where:

$\varnothing CCR_S$ = average curvature change rate of the single curves across the section under consideration without regarding tangents [gon/km] ,
CCR_{Si} = curvature change rate of the i-th curve [gon/km] ,
L_i = length of the i-th curve [m].

This average $\varnothing CCR_S$-value will be substantially higher than that applying to large radii curves and exceeded in the case of small radii curves. However, since the design speed should be constant on relatively long sections, it makes sense to apply the average curvature change rate to estimate the design speed. This average $\varnothing CCR_S$-value is input into Eq. 3 in order to calculate the average ∅V85, which is then considered as an estimate of the design speed. If the terrain is hilly to mountainous with gradients in excess of 6 percent, it may be more appropriate to use Eq. 4 in the estimation of the design speed (10). In doing so, it can be assumed that for this design speed over- and under-dimensionings of existing elements may even be avoided, that they even can be adapted to each other and can be optimized to a certain extent from the viewpoints of economic, environmental and safety related issues. The practical application of the procedure is presented in the Case Study of Table 4.

Operating Speeds

Curves

In the case of new designs, redesigns or RRR-strategies, it is necessary to estimate the 85th-percentile speed (operating speed) for each curve. Operating speed backgrounds, which can be used for estimation of the operating speed on individual curves, were derived for eight countries. These are Australia, Canada, France, Germany, Greece, Italy, Lebanon, and the United States (9, 11). Across the entire range of CCR_S, Italy offers the highest operating speed (12) and Lebanon the lowest. By regression analysis sound average relationships between CCR_S and V85 could be developed for worldwide application with respect to the longitudinal grade. The future equations read, as follows:

V85 for longitudinal grades G ≤ 6 % and CCR_S-values between 0 and 1600 gon/km (13, 14)

$$V85 = 105.31 + 2 \cdot 10^{-5} \cdot CCR_S^{\,2} - 0.071 \cdot CCR_S \qquad R^2 = 0.98 \qquad \text{(Eq. 3)}$$

V85 for longitudinal grades G > 6 % and CCR_S-values between 0 and 1600 gon/km (15)

$$V85 = 86 - 3.24 \cdot 10^{-9} \cdot CCR_S^{\,3} + 1.61 \cdot 10^{-5} \cdot CCR_S^{\,2} - 4.26 \cdot 10^{-2} \cdot CCR_S \qquad R^2 = 0.88 \qquad \text{(Eq. 4)}$$

Both relationships apply to CCR_S-values between 0 (corresponding to a tangent) and 1600 gon/km (corresponding to a radius of about 40 m without considering transition curves). They suggest that, on gradients less than 6 %, the operating speed on long tangents will be of the order of 105 km/h on average and 86 km/h on the steeper gradients (10). Individual relationships between CCR_S and V85 for the above mentioned countries can be found in (9) und (11).

Tangents

It was previously stated that three possible cases have to be considered according to Figure 1:

Case 1: $TL \leq TL_{min}$

(non-independent tangent, not considered in the safety evaluation process, the sequence curve-to-curve is relevant).

Case 2: $TL \geq TL_{max}$

(independent tangent, considered in the safety evaluation process, the sequence tangent-to-curve is relevant).

Case 3: $TL_{min} < TL < TL_{max}$

(independent tangent, considered in the safety evaluation process, the sequence tangent-to-curve is relevant).

In order to determine the appropriate operating speed and whether a tangent is to be considered as being independent or non-independent, the tangent length is evaluated in relation to TL_{min} and TL_{max} (Figure 1). It is thus necessary to calculate values of TL_{min} and TL_{max}. This calculation is based on an average acceleration or deceleration rate of $a = 0.85\ m/s^2$, which was established by application of car-following techniques (9). The following formulas go back to the fundamental equation for the evaluation of the transition lengths between two successive curves according to Eq. 5:

Case 1: For $TL \leq TL_{min} \rightarrow$ non-independent tangent, (Fig. 1):

$$TL_{min} = \frac{\left|(V85_1)^2 - (V85_2)^2\right|}{2 \cdot 3.6^2 \cdot a} \qquad \text{(Eq. 5)}$$

$$TL_{min} = \frac{\left|(V85_1)^2 - (V85_2)^2\right|}{22.03} \qquad \text{(Eq. 5a)}$$

In Eqs. 5 and 5a, $TL \leq TL_{min}$ means that the existing tangent is, at most, the length which is necessary for adapting the operating speeds between curves 1 and 2. In this case, the element sequence curve-to-curve, and not the intervening (non-independent) tangent, controls the evaluation process according to Safety Criterion II for differentiating between good, fair, and poor design practices (Table 2).

Case 2: For $TL \geq TL_{max} \rightarrow$ independent tangent, (Fig. 1):

$$TL_{max} = \frac{(V85_{Tmax})^2 - (V85_1)^2}{2 \cdot 3.6^2 \cdot a} + \frac{(V85_{Tmax})^2 - (V85_2)^2}{2 \cdot 3.6^2 \cdot a} \qquad \text{(Eq. 6)}$$

$$TL_{max} = \frac{2 \cdot (V85_{Tmax})^2 - (V85_1)^2 - (V85_2)^2}{22.03} \qquad \text{(Eq. 6a)}$$

In Eqs. 6 and 6a, $TL \geq TL_{max}$ means that the existing tangent is long enough to allow acceleration up to the maximum operating speed ($V85_{Tmax}$) on tangents. In this case, the element sequences independent tangent-to-curve or curve-to-independent tangent become relevant for the evaluation of Safety Criterion II in Table 2. (For the definition of the symbols, see Fig. 1).

Case 3: For $TL_{min} < TL < TL_{max} \rightarrow$ independent tangent, (Fig. 1):

$$\frac{TL - TL_{min}}{2} = \frac{(V85_T)^2 - (V85_1)^2}{22.03} \qquad \text{for } V85_1 > V85_2 \qquad \text{(Eq. 7)}$$

$$\Leftrightarrow \; V85_T = \sqrt{11.016 \cdot (TL - TL_{min}) + (V85_1)^2} \qquad \text{(Eq. 7a)}$$

The existing tangent length lies somewhere between TL_{min} and TL_{max}. Although the tangent segment does not allow accelerations up to the highest operating speed ($V85_{Tmax}$), additional acceleration and deceleration maneuvers are possible (see Fig. 1). In this case, the tangent speed ($V85_T$), which can be attained, has to be calculated according to Eq. 7a for the evaluation of Safety Criterion II. (For the definition of the symbols, see Fig. 1. Always use the larger value of $V85_{1,2}$).

Friction-Related Criterion

Pavement skid resistance applies to sight distance in all its forms, such as stopping sight distance, passing sight distance, barrier sight distance, intersection sight distance, etc. Side friction supports superelevation in providing a balance between the centrifugal and centripetal forces operating on a vehicle, while it is traversing a curve. In short, there must, in addition to the other forms of consistency, also be consistency in the driving dynamics at curved sites.

Criterion III was introduced to address this aspect of design consistency and relates to the difference between the side friction assumed for design and that actually demanded at the operating, or 85th-percentile speed level. While, for good design, Criterion I requires that the 85th-percentile speeds along the observed road segment should not deviate too markedly from that appropriate to the design speed, and Criterion II allows only limited deviation between operating speeds on successive design elements, Criterion III demands that each curve individually should also be safe (10).

According to Table 2, Safety Criterion III compares side friction assumed (f_{RA}) for curve design with side friction demanded (f_{RD}) for cars riding through the curve at the 85th-percentile speed level. Based on the analyses of skid resistance databases in Germany, Greece and the United States, and the maximum permissible tangential friction factors in the guidelines of selected countries (U.S.A., Germany, France, Sweden and Switzerland), tangential friction (f_T) is modeled by the expression of Equation 8 in Table 3 for modern highway geometric design. Meanwhile the criteria for tangential friction factors of 9 different countries worldwide, listed in the "Highway Design and Traffic Safety Engineering Handbook" (9) and developed by Harwood et al. (16) are known, and were taken as the basis for a new regression model with respect to tangential friction. The new formula reads:

$$f_T = 0.58 - 4.92 \cdot 10^{-3} \cdot V_d + 1.81 \cdot 10^{-5} \cdot V_d^{\,2} \qquad \text{(Eq. 8a)}$$

Comparing Equations 8 in Table 3 and 8a reveals, that there exist only insignificant differences. Thus, Equation 8 can be furthermore acknowledged as sound for the application of Safety Criterion III.

The side friction assumed is a fraction of tangential friction and corresponds to Equation 9 in Table 3, where “n” expresses the permissible utilization ratio for side friction assumed in comparison to tangential friction, and the factor 0.925 represents tire specific influences. As can be seen, different utilization ratios are suggested for new designs, separated according to hilly/mountainous and flat topography, as well as for existing (old) alignments, based on in-depth safety and economic considerations. Whereas, side friction assumed is related to the design speed (V_d), side friction demanded is related to the 85th-percentile speed (Eq. 10) with respect to the radius of curve and the superelevation rate of the investigated, individual curved site.

Quantitative ranges of values for the differences between side friction assumed (f_{RA}) and side friction demanded (f_{RD}) based on the above-mentioned databases, for good, fair (tolerable) and poor design practices are listed in Table 2.

Safety Evaluation Process

After knowing the design speed, the 85th-percentile speed as well as side friction assumed (f_{RA}) and demanded (f_{RD}), the safety evaluation process according to the ranges for the three Safety Criteria in Table 2 can be conducted. For a better understanding, one example (out of about fifty so far compiled and analyzed case studies) is demonstrated in Table 4. The old existing alignment in Greece consists of three curves (R = 245 m, R = -425 m, and R = 145 m) combined with two long independent tangents (510 and 555 m). According to the previously explained calculation process for the average $\varnothing CCR_S$ (Eq.2), a value of about 250 gon/km was found for the investigated roadway section. Based on the individual Greek operating speed background (Eq. 11) a $\varnothing CCR_S$ of 250 gon/km corresponds to an average 85th-percentile speed of $\varnothing V85 = 82$ km/h as basis for the estimation of a sound design speed of 90 km/h. Table 4 reveals now the safety evaluation process according to Table 2.

- As a result of the evaluation process of Safety Criterion I (Table 4), it can be shown, that the speed differences of all individual design elements (curves and independent (long) tangents) reveal good design with the exception of element 5 (fair design).
- With respect to Safety Criterion II the operating speed transitions between curve element 1 and the independent (long) tangent 2 fall into the fair range, whereas between independent tangent 4 and curve element 5 they fall into the poor range (see Table 4).
- Safety Criterion III (Table 4) reveals fair design for curve element 1 and poor design for curve element 5 according to Table 2.

COMPARATIVE ANALYSES OF THE ACTUAL ACCIDENT SITUATION WITH THE RESULTS OF THE SAFETY CRITERIA

In References (10-15, 17-19) it was demonstrated that the safety concept of the Institute for Highway and Railroad Engineering of the University of Karlsruhe, Germany (9), is appropriate for the safety classification of roadway sections according to good, fair (tolerable), and poor design practices and sensible results can be expected. The final goal of the above investigations was to show the level of agreement between the outcome of the three safety criteria and the actual accident situation, expressed by the accident rate (accident risk) and accident cost rate (accident severity). While SCHMIDT (17), EBERHARD (15) and ZUMKELLER (18) already demonstrated a strong tendency for a good agreement between safety criteria and accident rates, SCHNEIDER (19) was the first one, who was able to express a level of agreement in numbers. In Table 2 the symbols **“+”** (good design), **“o”** (fair design), and **“-“** (poor design) were already introduced for the three Safety Criteria. For comparative reasons SCHNEIDER (19) developed a similar system with respect to accident rates (Eq. 12) and accident cost rates (Eq. 13) to differ between a “low”, “medium” and “high” endangerment. In this connection he defined a low accident rate, if no more than 1 accident occurred on an element sequence (curved site or independent tangent), a medium accident situation, if no more than 2 accidents occurred, and a high accident situation, if more than 2 accidents were present within an investigation time period of three years. SCHNEIDER considered in his investigations the accident types “Run-Off-The-Road” and “Deer” accidents. Both types are directly related to the operating speed, and thus represent best the assumption of the Safety Criteria.

With respect to the accident cost rate the process is far more complicated, since here not only the number of accidents count, but the accident costs (either property damage or light, or severe, or fatal injury) play also an important role.

In order to consider Accident Rate (AR) and Accident Cost Rate (ACR), that means frequency and severity of traffic accidents, to the same extent, SCHNEIDER combined both rates, equally weighted, in a 3 by 3 matrix (Table 5), which represents three endangerment levels **(+, o, -)**, like the safety criteria (see Table 2). Thus, when Safety Criterion I, for example, reveals good design (symbol **"+"**) in Table 2 a level of **full agreement** is reached, if the combination of AR and ACR in Table 5 also shows the symbol **"+".** Or, if, for example, Safety Criterion III falls into the range of poor design (symbol **"-"**), a full agreement is reached, if the combination of AR and ACR shows the symbol **"-"**.

As **partial agreement** it is understood, if for example, a safety criterion reveals **"+"**, but the combination according to Table 5 results in an accident situation, which would be represented by the symbol **"o"**. A **disagreement** is defined, if the comparison between individual Safety Criteria and Table 5 differs for two steps, that means from **"+"** to **"-"** or vice versa. For the following counting of agreement percentages, full agreement is regarded by the weight "2", partial agreement by the weight "1" and disagreement by the weight "0". To strengthen statistically the findings RUSCHER (14) tried to examine once more the level of agreement between the Safety Criteria with the actual accident situation, based on new, independent and statistically sound databases. The investigations were related to 236 roadway sections, consisting of 2726 individual elements sequences (curved sites or independent tangents) with an overall length of 490 kilometers. For the evaluation of the ISE-Safety Concept with respect to a broad database, two cases with different accident types were investigated.

In the first case 1000 accidents of the types "Run-Off-The-Road" and "Deer" were included. In the second case 1384 accidents of the types "ROR", "Head-on/Rear end" and "Deer" were incorporated. With respect to the first case for Safety Criterion (SC) I a level of agreement of 81 %, for SC II of 77 % and for SC III of 72 % could be reached in comparison with the actual accident situation, expressed by the combination of accident rates and – cost rates according to Table 5. With respect to the additional accident type "Head-on/Rear end" in Case 2, the results revealed insignificantly lower levels of agreement. SC I reached here an agreement level of 79 %, SC II of 75 % and SC III of 71 %.

Thus, the research about the comparative analysis of the actual accident situation with the results of the safety criteria clearly has indicated a statistically significant relationship between the results of the three individual safety criteria and the actual accident rates to identify good (low endangerment), fair (medium endangerment) and poor (high endangerment) design practices. This is true for new designs, redesigns, and RRR-practices, as well as for the examination of existing (old) alignments.

CONCLUSION AND OUTLOOK

A methodology for controlling the alignment consistency has been developed. The methodology is based on the design parameter, Curvature Change Rate of the Single Curve. This parameter was tested against several databases of accident rates and accident cost rates and found to be the major descriptor of the safety of road alignments. The same is true with respect to operating speeds.

Furthermore, the two important speed terms (design- and operating speed) in modern highway geometric design and their impact on individual design elements were discussed. Based on these speed terms, quantitative ranges for three safety criteria were developed and associated with design classes for good, fair and poor practices with respect to accident research. The safety evaluation process expresses the need for achieving design-, operating speed-, and driving dynamic consistency.

Whereas, the term "operating speed (V85)" is nowadays well defined by the new design parameter curvature change rate of the single curve to describe the road characteristics, the "design speed" is often not known or was roughly assessed in the past for the overwhelming majority of existing roadways. Therefore, a new procedure, which takes into account the overall characteristics of the roadway, was developed in order to assign sound design speeds to old, existing, but also to new alignments.

Based on these design speeds, redesigns or RRR (Resurfacing, Restoration, and Rehabilitation)-projects can be made by changing the alignment to the extent necessary to remedy any detected individual or a combined safety problem (like design-, operating speed- or driving dynamic deficiencies), while regarding at the same time important economic and environmental issues. The procedure is explained by a case study.

Finally, the results of the three Safety Criteria are compared with the actual accident situation. The results confirmed in a convincing manner that a statistically significant relationship exists between the outcome of the three safety criteria and the actual accident rates.

By using the good ranges of the three safety criteria sound alignments in plan and profile can be achieved, which are well associated with the expected driving behavior of the motorists and may reduce significantly accident risk and -severity.

So far, accidents had first to occur, in order to find out that the spot or the roadway section is dangerous. The great advantage of the new Safety Concept is, that already in the design stages the safety criteria can predict the endangerment (low, medium, high) for new alignments. Additionally, they are also appropriate for statements about the safety conditions of existing (old) roadway sections or whole road-networks. In this way the highway- and traffic safety engineer is provided with quantitative tools, in order to evaluate the expected accident situation and to correct in advance deficiencies regarding new designs, or to plan in time sound countermeasures for highly endangered existing or old alignments.

REFERENCES

1. Lamm, R., E.M. Choueiri, J.C. Hayward, and A. Paluri. Possible Design Procedure to Promote Design Consistency in Highway Geometric Design on Two-Lane Rural Roads. In Transportation Reserarch Record 1195, TRB, National Research Council, Washington, D.C., 1988, pp. 111-122.

2. Lamm, R., E.M. Choueiri, and J.C. Hayward. Tangent as an Independent Design Element. In Transportation Reserarch Record 1195, TRB, National Research Council, Washington, D.C., 1988, pp. 123-131.

3. Leisch, J.E., and J.P. Leisch. New Concepts in Design Speed Application. In Transportaton Research Record 631, TRB, National Research Council, Washington, D.C., 1977, pp. 4-14.

4. Hayward, J.C. Highway Alignment and Superelevation: Some Design-Speed Misconceptions. In Transportation Research Record 757, TRB, National Research Council, Washington, D.C., 1980, pp. 22-25.

5. Koeppel, G., and H. Bock. Operating Speed as a Function of Curvature Change Rate. In Research Road Construction and Road Traffic Technique (Forschung Strassenbau und Strassenverkehrstechnik), Vol. 269, Minister of Transportation, Bonn, Germany, 1979.

6. Lamm, R. Driving Dynamics and Design Characteristics — A Contribution for Highway Design under Special Consideration of Operating Speeds. Thesis for Appointment as University Lecturer, Publications of the Institute for Highway and Railroad Engineering, Vol. 11, University of Karlsruhe (TH), Germany, 1973.

7. Bitzl, F. The Safety Level of Roads. In Research Road Construction and Road Traffic Technique (Forschung Strassenbau und Strassenverkehrstechnik), Vol. 28, Minister of Transportation, Bonn, Germany, 1964.

8. Krebs, H.G., and J.H. Kloeckner. Investigations of the Effect of Highway and Traffic Conditions Outside Built-Up Areas on Accident Rates. In Research Road Construction and Road Traffic Technique (Forschung Strassenbau und Strassenverkehrstechnik), Vol. 223, Minister of Transportation, Bonn, Germany, 1977, pp. 1-63.

9. Lamm, R., B. Psarianos, T. Mailaender, E.M. Choueiri, R. Heger, and R. Steyer. Highway Design and Traffic Safety Engineering Handbook. McGraw-Hill, Professional Book Group, New York, N.Y., U.S.A., 1999, 932 pages, ISBN 0-07-038295-6, Language Editors: J.C. Hayward, E.M. Choueiri, and J.A. Quay.

10. Lamm, R., K. Wolhuter, A. Beck, and T. Ruscher. Introduction of a New Approach to Geometric Design and Road Safety. Proceedings of the 20th Annual South African Transport Conference, 16 – 19 July, 2001, Pretoria, South Africa, pp., so far unknown.

11. Lamm, R., T. Ruscher, and A. Beck. Instructor’s Guide about the Practical Application of Quantitative Safety Criteria for Two-Lane Rural Roads. According to the “Highway Design and Traffic Safety Engineering Handbook”. Institute for Highway and Railroad Engineering, University of Karlsruhe (TH), Germany, Unpublished Manuscript, 2001.

12. Cafiso, S. Experimental Survey of Safety Conditions on Road Stretches with Alignment Inconsistencies. Proceedings of the 2nd International Symposium on Highway Design, Transporation Research Board (TRB), and Road and Transportation Research Association (FGSV), Mainz, Germany, June 14-June 16, 2000, Conference Proceedings, pp. 377-387.

13. Beck, A. Analysis and Evaluation of Relationships between Traffic Safety and Highway Design on Two-Lane Rural Roads. Master Thesis, Institute for Highway and Railroad Engineering, University of Karlsruhe (TH), Germany, 1998.

14. Ruscher, R. Evaluation of the Safety Concept of the Institute for Highway and Railroad Engineering (ISE) with the Actual Accident Situation for a Broad Data Basis. Master Thesis, Institute for Highway and Railroad Engineering, University of Karlsruhe (TH), Germany, 2001.

15. Eberhard, O. Development of an Operating Speed Background for Roadway Sections with Grades ≥ 6 Percent, as well as Analysis and Evaluation of Selected Road Sections, Based on Three Safety Criteria. Master Thesis, Institute for Highway and Railroad Engineering, University of Karlsruhe (TH), Germany, 1997.

16. Harwood, D.W., D.B. Fambro, B. Fishburn, H. Joubert, R. Lamm, and B. Psarianos. International Sight Distance Design Practices. International Symposium on Highway Geometric Design Practices, Transportation Research Board, Boston, Massachusetts, U.S.A., August 30 – September 1, 1995, Conference Proceedings, 1998, pp. 32-1 to 32-23.

17. Schmidt, G. Analyses and Evaluation of Roadway Sections with Respect of Three Safety Criteria. Master Thesis, Institute for Highway and Railroad Engineering, University of Karlsruhe (TH), Germany, 1995.

18. Zumkeller, K. Analysis and Evaluation of Possible Relationships between Traffic Safety, Road Design and Road Equipment with Road Markings, Traffic Control Devices and Guardrails. Master Thesis, Institute for Highway and Railroad Engineering, University of Karlsruhe (TH), Germany, 1998.

19. Schneider, B. Development of a Superior Safety Module for the Evaluation of the Danger of Two-Lane Rural Roads in Tune with the Actual Accident Situation. Master Thesis, Institute for Highway and Railroad Engineering, University of Karlsruhe (TH), Germany, 1999.

LIST OF TABLES

TABLE 1: t-Test Results of Mean Accident Rates for Different CCR$_S$-Classes for Germany (West) and for the U.S.A. (9, 11)

Design/ CCR$_S$-classes [gon/km]	**Mean AR**	**$t_{calc.}$ $t_{crit.}$**	**Significance; Remarks**
Database 1: United States of America (261 Two-Lane Rural Test Sites), 1987 Including all Accidents			
			Considered as
tangent (0)	1.17		--- Good Design
		4.00 > 1.96	Yes
35 – 180	2.29		--- Good design
		7.03 > 1.96	Yes
> 180 – 360	5.03		--- Fair design
		6.06 > 1.99	Yes
> 360 – 550	10.97		--- Poor design
		3.44 > 1.99	Yes
> 550 – 990	16.51		--- Poor design
Database 2: Germany (657 Two-Lane Rural Test Sites), 1994 Including Run-Off-The Road-, and Deer Accidents			
			Considered as
tangent (0)	0.35		--- Good Design
		5.20 > 1.99	Yes
35 – 180	0.51		--- Good design
		10.70 > 1.96	Yes
> 180 – 360	1.72		--- Fair design
		2.64 > 1.98	Yes
> 360 – 550	2.78		--- Poor design

Database 3: Germany (2726 Two-Lane Rural Test Sites), 2001 **Including Run-Off-The Road-, and Deer Accidents**			
			Considered as
0 - 180	0.22		--- Good design
		27.92 > 1.65	Yes
> 180 - 360	0.87		--- Fair design
		15.69 > 1.65	Yes
> 360	2.27		--- Poor design
Database 3: Germany (2726 Two-Lane Rural Test Sites), 2001 **Including Run-Off-The-Road-, Head-on-, and Deer Accidents**			
			Considered as
0 - 180	0.33		--- Good design
		28.04 > 1.65	Yes
> 180 - 360	1.12		--- Fair design
		14.09 > 1.65	Yes
> 360	2.52		--- Poor design

Legend:

AR = accident rate (acc. per 10^6 veh.-km) according to Eq. (11) in Table 5.

TABLE 2: Quantitative Ranges for Safety Criteria I to III for Good, Fair, and Poor Design Classes (9, 11)

Safety Criterion	**DESIGN (CCR_S)-CLASSES**		
	GOOD (+)	**FAIR (o)**	**POOR (-)**
	Permissible Differences $\lvert CCR_{Si} - CCR_{Si+1} \rvert \leq 180$ gon/km	Tolerated Differences 180 gon/km $< \lvert CCR_{Si} - CCR_{Si+1} \rvert \leq 360$ gon/km	Non-Permissible Differences $\lvert CCR_{Si} - CCR_{Si+1} \rvert > 360$ gon/km
I[1)]	$\lvert V85_i - V_d \rvert \leq 10$ km/h	10 km/h $< \lvert V85_i - V_d \rvert \leq 20$ km/h	$\lvert V85_i - V_d \rvert > 20$ km/h
II[2)]	$\lvert V85_i - V85_{i+1} \rvert \leq 10$ km/h	10 km/h $< \lvert V85_i - V85_{i+1} \rvert \leq 20$ km/h	$\lvert V85_i - V85_{i+1} \rvert > 20$ km/h
III[3)]	$+0.01 \leq f_{RA} - f_{RD}$	$-0.04 \leq f_{RA} - f_{RD} < +0.01$	$f_{RA} - f_{RD} < -0.04$

Legend:

1) Related to the individual design elements "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 curve.

Note:

CCR_S = curvature change rate of the single curve [gon/km] ,
V_d = design speed [km/h] ,
$V85_i$ = expected 85th-percentile speed of design element "i" [km/h] ,
f_{RA} = side friction "assumed" [-] ,
f_{RD} = side friction "demanded" [-] .

TABLE 3: Listing of Formulas with Respect to Safety Criterion III (9)

f_T = tangential friction factor in modern highway geometric design [-]

= $0.59 - 4.85 \cdot 10^{-3} \cdot V_d + 1.51 \cdot 10^{-5} \cdot V_d^2$ (Eq. 8)

f_{RA} = side friction "assumed" [-]

= $n \cdot 0.925 \cdot f_T$ (Eq. 9)

n = utilization ratio of side friction [%/100]

= 0.40 for hilly/mountainous topography; new designs

= 0.45 for flat topography; new designs

= 0.60 for existing (old) alignments

f_{RD} = side friction "demanded" [-]

$$= \frac{V85^2}{127 \cdot R} - e \qquad \text{(Eq. 10)}$$

R = radius in the observed circular curve [m]

e = superelevation rate [%/100]

TABLE 4: CASE STUDY FOR AN EXISTING ALIGNMENT AND SAFETY EVALUATION PROCESS IN GREECE (9)

Element	Design Element[1)]	Length L_i	CCR_{Si}	e	$V_d \approx \varnothing V85$	$V85_i$[2)]	Safety Criterion I $\lvert V85_i - V_d \rvert$	Safety Criterion II $\lvert V85_i - V85_{i+1} \rvert$	Safety[4)] Criterion III $f_{RA} - f_{RD}$
no.	[m]	[m]	[gon/km]	[%]	[km/h]	[km/h]	[km/h]	[km/h]	[-]
1	R = 245	155	260	3.5	90	81	9 (good)	17 (fair)	-0.02 (fair)
2	R = ∞	510[3)]	0	2.0	90	98	8 (good)	10 (good)	–
3	R = -425	195	149	2.5	90	88	2 (good)	10 (good)	+0.03 (good)
4	R = ∞	555[3)]	0	2.0	90	98	8 (good)	26 (poor)	–
5	R = 145	100	439	4.5	90	72	18 (fair)		- 0.08 (poor)

Legend:

1) No transition curves present.
2) $V85_i$ based on the individual operating speed background of Greece
   $V85 = 10^6/(10150.1 + 8.529 \cdot CCR_S)$ (Eq. 11).
3) Independent (long) tangents $V85_{Tmax}$ has to be calculated for CCR_S = 0 gon/km .
4) n = utilization ratio of side friction. For existing alignments: n = 0.6 .

$$\varnothing CCR_S = \frac{155 \cdot 260 + 195 \cdot 149 + 100 \cdot 439}{155 + 195 + 100} \approx 250 \text{ gon/km} \rightarrow \varnothing V85 \approx 82 \text{ km/h} \Rightarrow V_d = 90 \text{ km/h (selected)} .$$

TABLE 5: Combination of Accident Rates and Accident Cost Rates for Different Endangerment Levels (19)

			ACR		
			low	**medium**	**high**
			+	**o**	**-**
AR	**low**	+	+	+	o
	medium	**o**	+	o	-
	high	**-**	o	-	-

Legend:

$$AR = \frac{\text{accidents} \cdot 10^6}{AADT \cdot 365 \cdot T \cdot L} \quad [\text{accidents per } 10^6 \text{ vehicle kilometers}] \qquad \text{(Eq. 12)}$$

where
AR = accident rate
AADT = average annual daily traffic, vehicles/24 h
L = length of the investigated section, km
T = length of the investigated time period, yr
365 = number of days/yr

$$ACR = \frac{S \cdot 100}{AADT \cdot 365 \cdot T \cdot L} \quad [\text{monetary unit per 100 vehicle kilometers}] \qquad \text{(Eq. 13)}$$

ACR = accident cost rate
S = sum of all property- and personal damages in the time period T observed (monetary unit of the country under study)

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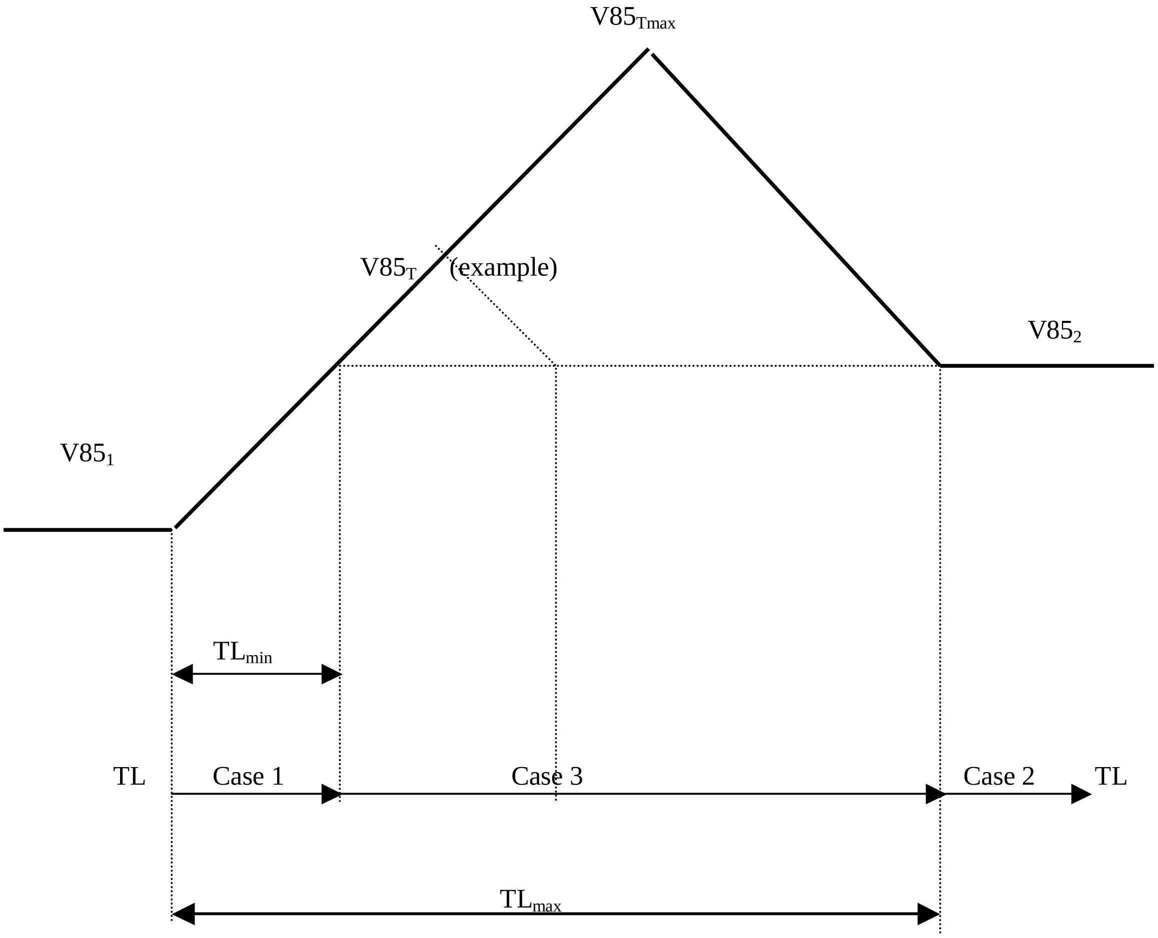

Legend:

$V85_{1,2}$ = 85th-percentile speeds in curves 1 and 2 [km/h],
$V85_{Tmax}$ = Maximum operating speed in tangents [km/h] for CCR_S = 0 gon/km (depending on Eqs. 3 and 4),
$V85_T$ = Operating speed in tangents [km/h] ($V85_T$ can maximum reach $V85_{Tmax}$),
TL = Existing tangent length between two successive curves [m],
TL_{min} = Necessary acceleration/deceleration length between curves 1 and 2 [m],
TL_{max} = Necessary acceleration/deceleration length to reach $V85_{Tmax}$ between curves 1 and 2 [m].

FIGURE 1: Systematic Sketch for Determining Tangent Speeds and Lengths in the Safety Evaluation Process (9, 11, 15)