Safety Index for Evaluation of Two-Lane Rural Highways

By:

Salvatore Cafiso
Associate Professor
Department of Civil and Environmental Engineering
University of Catania
Viale Andrea Doria 6, 95125 Catania, Italy
Phone: +39 0957382213
Fax: +39 0957382247
E-mail: dcafiso@dica.unict.it

Grazia La Cava
Ph.D., P.Eng.
Department of Civil and Environmental Engineering
University of Catania
Viale Andrea Doria 6, 95125 Catania, Italy
Phone: +39 0957382223
Fax: +39 0957382247
E-mail: glacava@dica.unict.it

Alfonso Montella
Ph.D., P.Eng., Assistant Professor
University of Naples Federico II
Department of Transportation Engineering "Luigi Tocchetti"
Via Claudio 21, 80125 Naples, Italy
Phone: +39 0817683941
Fax: +39 0817683946
E-mail: alfonso.montella@unina.it

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ABSTRACT

A methodological approach for the safety evaluation of two-lane rural highway segments that uses both analytical procedures referring to alignment design consistency models and safety inspection processes is presented. A safety index (SI) that quantitatively measures the relative safety performance of a road segment is calculated from the procedure. The SI is formulated by combining three components of risk: the exposure of road users to road hazards, the probability of a vehicle being involved in an accident and the resulting consequences should an accident occur.

This systematic and replicable procedure integrates two different, complementary approaches, one based on design consistency evaluations and the other on safety inspections, and makes it possible to effectively address a wide variety of safety issues. A further advantage of the procedure is its applicability on highways where crash data are either not available or are unreliable. Validation of the procedure was carried out on a sample of roads by a comparison of the risk rank obtained using the SI and accident history. The SI was assessed in 30 segments chosen from a sample of two-lane rural highways in Italy and the actual accident situation was obtained with the EB procedure. Spearman's rank-correlation was used to determine the level of agreement between the rankings obtained using the two techniques. The results from the Spearman's rank-correlation analysis validate the SI, indicating that the ranking from the SI scores and the EB estimates agree at the 99.9% level of significance with a correlation coefficient of 0.87.

Keywords: road safety inspections, design consistency, safety index, ranking criteria, EB procedure.

INTRODUCTION

Road safety evaluations on low and medium traffic rural two-lane highways can raise concerns both due to the general deficiency of reliable data on road accidents and to the circumstance that few accident data not always can give enough information on accidents to be prevented. Based on these considerations, a methodological approach for the safety evaluation of two-lane rural highways was defined which uses both analytical procedures referring to alignment design consistency models and the safety inspection process. The research was performed as part of the project "Identification of Hazard Locations and Ranking of Measures to Improve Safety on Local Rural Roads" (Italian acronym IASP), funded by the European Commission (DG TREN) and the Province of Catania (Italy) (*1*-5).

Many studies show that safety evaluations based on the analysis of alignment design consistency can be effective in identifying hazardous road locations (*6-7*). The proposed approach makes use of theoretical-experimental models for the evaluation of alignment design consistency. However, the resulting analyses, although effective in addressing alignment inconsistencies, do not highlight all the potential accident contributory factors. Hence, the IASP methodology integrates the results of the models with those deriving from the safety issues evaluation made during the Safety Inspection process.

Road Safety Inspections (RSI) are aimed at identifying potential hazards, which are assessed by measuring risk in relation to those road features that may lead to future accidents, so that remedial treatments may be implemented before accidents happen (*8*). Safety inspections are recognized as an effective tool and are becoming an accepted practice in many agencies around the world (*9-14*). Recent researches performed in British Columbia (*15*) and in Italy (*8*) have shown that road safety impact assessment based on RSIs can be effective. In order to use safety inspections as part of a quantitative safety evaluation process, the IASP project defined procedures and criteria for identifying and ranking safety issues (*2*). The ranking criteria take into account the road safety effects of the identified issues. The RSI, carried out according to these procedures, showed that there is a statistically-significant level of agreement (measured through the k test) between the safety issues evaluations produced by different inspectors, for the majority of the safety issues. A systematic and replicable safety inspection process allows a quantitative safety index (SI) to be assessed, based on the data obtained from the RSI combined with information from theoretical-experimental models.

FORMULATION OF THE SAFETY INDEX

The safety index (SI) measures the relative safety performance of a road segment. It does not take into account junctions and it refers to two-lane rural highways.

The SI is formulated by combining three components of risk: the exposure of road users to road hazards (Exposure factor), the probability of a vehicle being involved in an accident (Accident Frequency factor) and the resulting consequences should an accident occur (Accident Severity factor).

General formulation of SI is as follows:

$$SI = \text{Exposure factor} \times \text{Accident Frequency factor} \times \text{Accident Severity factor} \qquad (1)$$

Exposure Factor

The Exposure factor measures the exposure of road users to road hazards, and is assessed by equation 2 as follows:

$$\text{Exposure factor} = L \times AADT \qquad (2)$$

where:

L = length of the segment under consideration (km);

$AADT$ = average annual daily traffic [(1,000 vehicles per day)].

Accident Frequency Factor

The Accident Frequency factor depends on the safety features of the segment, which are assessed by two analysis methodologies:

- road safety inspections;
- design consistency evaluations and design standards check.

The Accident Frequency factor is obtained by the formula:

$$\text{Accident Frequency factor} = \text{RSI AF} \times \text{GD AF} \qquad (3)$$

where:

RSI AF = Road Safety Inspection Accident Frequency factor;

GD AF = Geometric Design Accident Frequency factor.

Road Safety Inspections

RSI procedures defined by the IASP research program are aimed at improving the effectiveness and reliability of the methodology (*2*). Indeed, even though safety evaluations based on inspections are subjective in nature, ranking of safety issues performed in 200 segments by two groups of safety specialists has shown that there is a statistically significant level of agreement among inspectors for the majority of the safety issues (*5*).

Rankings are carried out using checklists relating to the main safety features that may be consistently present along two-lane rural roads. Checklists are filled in for both directions of the road, with a step of 200 m. Procedures and criteria for identifying and ranking safety issues were defined (see Table 1) (*2*, *3*). Safety issues are ranked as ‘high level problem’ (score equal to 1), ‘low level problem’ (score equal to 0.5) and ‘no problem’ (score equal to 0).

The following safety issues are assessed using defined criteria: accesses, cross section, delineation, markings, pavement, roadside, sight distance, signs. In order to improve the evaluation of safety issues, each item is divided into more detail (see Table 1).

TABLE 1 Safety Issues of Road Safety Inspections

Safety Issue	**Detailed Safety Issue**	**Main Criteria for Identifying High Level Problems ($S_{ik} = 1$)**	**Main Criteria for Identifying Low Level Problems ($S_{ik} = 0.5$)**
Accesses	Dangerousness of accesses	Location on horizontal curves, on crests, on sites with poor visibility, close to intersections	Unpaved accesses, narrow accesses
	Density of accesses	Three or more accesses in one 200 m long stretch	One or two accesses in one 200 m long stretch
Cross section	Lane width	L<2.75 m; L>4.50 m	2.75≤L<3.25 m; 3.75<L≤ 4.50 m
	Shoulder width	Width < 0.30 m	0.30 ≤ Width < 1.00 m
Delineation	Chevrons	Missing chevrons on severe curves	Missing chevrons on moderate curves
		Chevron placement or visibility inadequate to give correct perception of the curve	Partially obscured chevrons Low reflective chevrons
	Guideposts and barrier reflectors	Missing guideposts Missing reflectors on guideposts, on roadside safety barriers or on roadside walls	Variable height of reflectors along the road Low reflective guideposts Local discontinuity of guideposts
Markings	Edge lines	Missing edge lines Very faded edge lines	Slightly faded edge lines Edge lines partially obscured by the vegetation
	Center line	Missing center line Very faded center line	Slightly faded center line
Pavement	Friction	Polished aggregate, bleeding, raveling, low macro-texture	Not defined, friction is ranked as high level problem or no problem
	Unevenness	Potholes, rutting, patches, shoving on curves or close to intersections	Little shoving, shallow potholes, rutting, patches on tangents
Roadside	Embankments	Unshielded embankments with great slope (h>3 m, i ≥ 2/3)	Unshielded embankments with medium slope (h>3 m, 1/3 ≤ i < 2/3)
	Bridges	Ineffective barriers	Medium containment barriers if the bridge overpasses roads or railways
	Dangerous terminals and transitions	No breakaway terminals (fish tails, buried in the ground, etc.)	Inadequate transition between steel barriers
	Trees, utility poles and rigid obstacles	High diameter trees or rigid obstacles located less than 3 m from carriageway	High diameter trees or rigid obstacles located between 3 and 8 m from carriageway
	Ditches	Rectangular or trapezoidal ditches located less than 3 m from carriageway	Rectangular or trapezoidal ditches located between 3 and 5 m from carriageway
Sight distance	Inadequate sight distance on horizontal curve	Available sight distance less than 50 m caused by continuous obstructions to visibility inside the curve	Available sight distance greater than 50 m but less than SSD or inadequate to give the correct road perception
	Inadequate sight distance on vertical curve	Available sight distance less than 50 m	Available sight distance greater than 50 m but less than SSD or inadequate to give the correct road perception
Signs	Warning signs, regulation signs	Missing curve and/or crest warning sign	Curve and/or crest warning sign faded or with low visibility

Using scores assigned to each inspection unit (segment 200 m long) during the survey, a weighted score of each safety issue j (WS_j), ranging from 0 to 1, is computed by the formula:

$$\mathrm{WS_j} = \frac{1}{2 \times \mathrm{n} \times m_j} \times \sum_{i=1}^{m_j} \sum_{k=1}^{2\times n} S_{ik} \tag{4}$$

where:

S_{ik} = score of the detailed safety issue i in the inspection unit k;
n = number of inspection units which form the section under consideration;
m_j = number of detailed issues associated with the issue j;
2 = factor to take both directions into account.

For each safety issue j the related Accident Frequency factor (AF_j) is computed by the formula:

$$AF_j = 1 + WS_j \times \Delta AF_j \times P_j \tag{5}$$

where:

ΔAF_j = estimated relative increase in accident risk due to the issue j;
P_j = proportion of accidents typologies affected by the issue j.

The cumulative influence of all the safety issues j is assessed by the RSI Accident Frequency factor, computed as follows:

$$\mathrm{RSI\ AF} = \prod_{j=1}^{\ell} \mathrm{AF_j} \tag{6}$$

where:

ℓ = number of safety issues, equal to 8 in the IASP model.

Based on existing literature, the relative increase in accident risk due to each issue was estimated (see Table 2).

TABLE 2 Safety Effects of the Issues

Safety Issue	Related Accidents	ΔAF (%)
Accesses	All	135
Cross section	Run off the road Head-on Sideswipe	15 - 100 f(AADT)
Delineation	All	30
Markings	All	20
Pavement	All	10
Roadside	Run off the road	0
Sight distance	All	50
Signs	All	20

Many studies have been performed to estimate the safety impact of various types of engineering improvement. Many existing Accident Modification Factors (AMFs) are derived from before–after analysis of actual countermeasure implementation. Indeed, such before–after studies, as opposed to cross-sectional/regression-type analysis, will produce the best AMF estimates, but only if conducted properly (*16*). Unfortunately, many current studies reflect changes in crash experience resulting from improvements at sites that had experienced unusually high accident rates in the before-treatment period. The selection bias inherent in this approach often results in significantly exaggerated AMF estimates due to the phenomenon of regression to the mean. The most accurate AMFs have been developed in rigorous before–after studies that incorporated the current best study design and statistical analysis methods. At this time, the empirical Bayes (EB) methodology represents the best available approach (*17-19*).

Change in accident risk (ΔAF_j) is related to the Accident Modification Factor (AMF_j) of the safety issue by the formula:

$$\Delta AF_j = AMF_j - 1 \tag{7}$$

Below, explanations of the relative increase in accident risk estimates for each safety issue are briefly reported.

Accesses Direct accesses to roads can significantly increase accidents. The location of access points (e.g., accesses on horizontal curves) can be very dangerous. AMFs that take into account driveway density have been developed (*20*): they show the dramatic effect of accesses on road safety. The ΔAF relative to a high frequency of dangerous accesses (40 accesses/km) is equal to 135%.

Cross section Cross section width affects single vehicle, run-off-the-road and multiple vehicle, head-on, opposite-direction sideswipe and same-direction sideswipe accidents (*20, 21*). The greater the lane and shoulder widths, the fewer the accidents. A bottom value in the lane width exists: too-wide lanes may be counter-productive (*6, 22*). The effect of cross section width is more pronounced for high traffic volumes and is assessed on the basis of the AMFs reported in (*20*). If AADT is greater than 2,000 vpd, very narrow lanes and shoulders, compared with ideal lanes and shoulders, increase related accident probability by 100%. If AADT is less than 400 vpd, the increase in related accident probability is 15%. With intermediate AADT values, the ΔAF varies linearly between these extreme values.

Delineation Daytime delineation of the road can generally be effectively accomplished with pavement markings. Night-time and rainy conditions, however, often require a different approach to provide long-range delineation of the roadway alignment (*23*). Supplementary delineation is an important safety factor in any condition; on horizontal curves, especially isolated curves with a short radius, it is critical. The chevron alignment sign is an important traffic control device used to warn drivers of the severity of a curve by delineating the alignment of the road around that curve (*24*). Missing or ineffective chevrons and damaged or missing guideposts or barrier reflectors can lead to an accident risk increase equal to 30% (*12*).

Markings A great deal of literature has investigated the effect of road markings on accidents, showing that their improvement is likely to be cost-effective (*10*, *12*, *25-28*). Relative increase in accident risk was assumed equal to 20% for missing or ineffective edge lines and center line.

Pavement The pavement factor which has the greatest impact on road safety is friction. The skid resistance of the road surface is an important safety factor, especially when the surface is wet. Several studies (*29*) show an increase in accident risk when the friction decreases below certain threshold values. Unevenness also affects road safety, although friction effect has been proved by more studies. The ΔAF relative to inadequate evenness and friction was selected as equal to 10%.

Roadside The main effect of roadside safety issues is not on accident probability but on accident severity. Therefore, the roadside is computed in the consequence factor of the risk model.

Sight distance Inadequate sight distance on horizontal and vertical curves is a common accident contributory factor. Literature reports widely different values related to the effect of sight distance improvement measures (*30-31*). Taking into account this variability, the ΔAF relative to inadequate sight distance on both horizontal and vertical curves was selected as equal to 50%.

Signs The road signs that have the greatest effect on traffic safety are warning signs (*32*). They call attention to unexpected conditions and to situations that might not be readily apparent to road users, giving suggestions about safe behavior. Regulatory signs, such as speed limits, can affect road safety by conveying essential information on safe behavior. For missing or ineffective signs, the relative risk factor was assumed as equal to 20% (*33*).

Design Consistency Evaluations and Design Standards Check

A consistent highway design ensures that successive elements are coordinated in such a way as to produce harmonious and homogeneous driver performances along the road. Practice highlights that an alignment with inconsistencies requires drivers to handle speed gradients in order to drive safely on certain alignment elements. On this basis, the importance of identifying inconsistencies on highways and its significant contribution to road safety is emerging as an important feature in highway design.

Design consistency evaluates an overall Safety Module (*6*, *7, 34*) defining three design classes: poor, fair, good. This Safety Module combines the following three safety criteria (see Table 3):

1. design consistency, related to the difference between the operating speed, represented by the 85th percentile speed (V_{85}), and the design speed (V_d) of the observed roadway section;
2. operating speed consistency, related to the difference in V_{85}, between two, successive, geometric elements;

3. driving dynamic consistency, determined by the difference between side friction assumed (f_{RA}, that depends on the design speed) and demanded (f_{RD}, that depends on the operating speed) on one individual curve.

TABLE 3 Quantitative Ranges for Safety Criteria I to III for Good, Fair, and Poor Design Classes

Safety Criterion	Design Classes		
	Good	Fair	Poor
I	$\lvert V_{85i} - V_d \rvert \leq 10$ km/h	10 km/h $< \lvert V_{85i} - V_d \rvert \leq 20$ km/h	$\lvert V_{85i} - V_d \rvert > 20$ km/h
II	$\lvert V_{85i} - V_{85i+1} \rvert \leq 10$ km/h	10 km/h $< \lvert V_{85i} - V_{85i+1} \rvert \leq 20$ km/h	$\lvert V_{85i} - V_{85i+1} \rvert > 20$ km/h
III	$f_{RA} - f_{RD} \geq + 0.01$	$- 0.04 \leq f_{RA} - f_{RD} < + 0.01$	$f_{RA} - f_{RD} < - 0.04$

$f_{RA} = 0.6 \times 0.925 \times (0.59 - 4.85 \times 10^{-3} \times V_d + 1.51 \times 10^{-5} \times V_d^2)$
$f_{RD} = V_{85}^2/(127 \times R) - e$

In order to evaluate the Safety Module, good design is classified by the weighting factor of "+1", fair design is described by the factor "0" and for poor design the factor "-1" is used. Summing up the weighting factors for the individual safety criteria, the calculated, average value *x* represents an evaluation for the safety module as shown in the following: if $x \geq 0.5$ design class is good; if $- 0.5 < x < 0.5$ design class is fair; if $x \leq - 0.5$ design class is poor.

Safety criteria evaluation is strictly related to the operating-speed profile. Operating speed can be evaluated using experimental, regression models. Considering that driver behavior and operating speed is influenced by national and environmental factors (*6*), as part of the research project two experimental regression models were developed for local two-lane rural highways:

$$V_{85} = 99.31 - 0.51 \times CD \qquad \text{(flat environment)} \qquad (8)$$

$$V_{85} = 82.76 - 0.45 \times CD \qquad \text{(mountain environment)} \qquad (9)$$

where:

$CD = \dfrac{360 \times 100}{2 \times \pi \times R}$ = curvature degree (°/100 m);
R = radius of the curve (m).

Regression models were obtained from a survey of actual vehicle operating speeds. The measurements were carried out with a dual-beam laser instrument located transversely across the road. In order to achieve a precision of 1.5 km/h in the estimation of the average speed, at a confidence level of 95% for each section, at least three hundred "isolated" vehicles were measured in good weather and daylight conditions. The measurements were carried out at the midpoint of the curves and at the midpoint of the long tangent between curves.

The Safety Module was used to check the consistency of curves. With regard to the safety concerns related to long or short tangents, two design standards checks were carried out according to the criteria defined in the Italian Standards (*35*): 1) maximum length of tangents (TL_{max}); 2) minimum length of tangents (TL_{min}). In order to avoid fatigue and glare from oncoming headlights during night driving, standards require a maximum length of tangents equal to 22 times the speed design (km/h) of the stretch under analysis. In order to perceive the straight element as a tangent, standards suggest a minimum tangent length that depends on the design speed (V_d = 60 km/h, TL_{min} = 50 m; V_d = 80 km/h, TL_{min} = 90 m; V_d = 100 km/h, TL_{min} = 150 m).

The Geometric Design Accident Frequency factor (GD AF) is assessed by the formula:

$$\text{GD AF} = 1 + WS_{GD} \times \Delta AF_{GD} \times P_{GD} \tag{10}$$

where:

WS_{GD} = weighted score of the safety issue GD;
ΔAF_{GD} = estimated relative increase in accident risk due to the issue GD;
P_{GD} = proportion of accidents affected by the issue GD.

For a section of ν geometrical elements, WS_{GD} is computed through a weighted mean of GDS_ℓ :

$$WS_{GD} = \frac{\sum_{\ell=1}^{\nu} GDS_\ell \times L_\ell}{\sum_{\ell=1}^{\nu} L_\ell} \tag{11}$$

where:
ν = number of geometrical elements that form the section under consideration;
L_ℓ = length of the geometrical element ℓ;
GDS_ℓ = Geometric Design Score of element ℓ.

Each GDS_ℓ (ranging from 0 to 1) was estimated (Table 4) by analyzing the increase of the accident rate with respect to:

- poor, fair and good Design Class for the curved elements;
- a check, in terms of minimum or maximum length, which failed Italian design standards (*35*) for tangents.

TABLE 4 Geometric Design Scores (GDS_ℓ)

Curved Elements		Tangents		Related Accidents
Good	0.2	Overall Standards Check	0.0	Run off the road
Fair	0.5	Minimum Length	0.1	Partially (50%):
Poor	1.0	Maximum length	0.1	Head-on
				Same direction and opposite direction sideswipe

The state of the art (*7*) indicates an increase in accident risk on poor curved segments as compared to tangents (ΔAF_{DCS}) equal to 700%.

Accident Severity Factor

Accident Severity is intended as a measure of the ratio between the number of severe accidents (injury or fatal) and the total number of accidents. Two factors were considered significant:

1) operating speed;
2) roadside hazard.

The Accident Severity factor for the segment is computed with the following formula:

$$\text{Accident Severity factor} = \left(\frac{V_{85}}{V_{base}}\right) \times \text{RSI AS}_{roadside} \tag{12}$$

where:

V_{85} = average 85th percentile of speed along the segment (weighted to element length);
V_{base} = base operating speed for two-lane, local, rural highways (assumed equal to the legal speed limit of 90 km/h);
RSI $AS_{roadside}$ = Roadside Accident Severity factor of the segment.

Road Safety Inspection Accident Severity factor of the roadside safety issue (RSI $AS_{roadside}$) is equal to:

$$\text{RSI AS}_{roadside} = 1 + WS_{roadside} \times P_{roadside} \times \Delta AS_{roadside} \tag{13}$$

where:

$WS_{roadside}$ = weighted score of the roadside safety issue;
$P_{roadside}$ = proportion of accidents related to the roadside issue, equal to the proportion of run off the road accidents;
$\Delta AS_{roadside}$ = estimated relative increase in accident severity due to the issue j. This value was assumed equal to 2 considering the maximum increase in proportion of injury accidents due to roadside hazard (29, 36).

Considering that RSI $AS_{roadside}$ evaluates roadside items including embankments, bridges, dangerous barrier terminals and transitions, trees, utility poles and rigid obstacles and ditches, a weighted mean of the roadside issue ($WS_{roadside}$) is computed as follows:

$$WS_{roadside} = \frac{\sum_{k=1}^{2\times n} \max_i (Score_{ik} \times Weight_i)}{2 \times n \times 5} \tag{14}$$

where:

$Score_{ik}$ = score of the roadside safety items i in the inspection units k (0, 0.5 or 1);
$Weight_i$ = relative weight of the roadside safety item i (see Table 5).

TABLE 5 Relative Weights of the Roadside Safety Items

Detailed Safety Issue	Relative Weight
Embankments	3
Bridges	5
Dangerous terminals and transitions	2
Trees, utility poles and rigid obstacles	2
Ditches	1

Relative increase in accident severity was calculated by using the AASHTO severity indices (*36*). In relation to design speed, which has been selected as equal to 90 km/h, severity indices for each roadside feature define the probability of injuries and fatalities, in the case of an accident. Based on accident severities corresponding to high level problems (see Table 1), the different weights of the roadside issues shown in Table 5 were established.

An example real-world application of the procedure is presented in Table 6.

TABLE 6 Example Real-World Application of Procedure (Road SP4II, Section 1)

L (km)				3.463			
AADT [(1,000 vehicles per day)]				4.10			
Exposure factor = L × AADT				**14.197**			
	Accesses	Cross Section	Delineation	Markings	Pavement	Sight Distance	Signs
WS_j	0.287	0.147	0.618	1.000	0.037	0.066	0.015
ΔAF_j	1.350	1.000	0.300	0.200	0.100	0.500	0.200
P_j	1.000	0.600	1.000	1.000	1.000	1.000	1.000
$AF_j=1+WS_j\times\Delta AF_j\times P_j$	1.387	1.088	1.185	1.200	1.004	1.033	1.003
$RSIAF=\prod AF_j$				2.233			
WS_{GD}				0.064			
ΔAF_{GD}				7.000			
P_{GD}				0.450			
$GDAF=1+WS_{GD}\times\Delta AF_{GD}\times P_{GD}$				1.202			
Accident Frequency factor = RSI AF × GD AF				**2.683**			
V_{85} (km/h)				76.94			
V_{base} (km/h)				90			
$WS_{roadside}$				0.253			
$P_{roadside}$				0.300			
$\Delta AS_{roadside}$				2.000			
$RSIAS_{roadside} = 1+WS_{roadside}\times P_{roadside}\times\Delta AS_{roadside}$				1.152			
Accident Severity factor = V_{85}/V_{base} × RSI $AS_{roadside}$				**0.985**			
SI = Exposure × Accident Frequency × Accident Severity				**37.505**			

VALIDATION OF PROCEDURE

In view of the complexity of the above-mentioned procedure, its validity was evaluated carrying out a pilot study.

Road Sample and Segmentation

A sample of about 100 km of two-lane, local, rural highways, located in the Province of Catania (Italy) was used in order to apply and validate the procedure. A segmentation into homogeneous sections was carried out on the basis of the geometric alignment characteristics and traffic flow volumes. Thirty homogeneous segments were obtained.

EB Estimates

A model that predicts road segment accident frequency, using the segment length and the AADT volume as explanatory variables, was developed with the data reported in Table 7. Generalized linear modeling techniques (GLIM) were used to fit the model, and a negative binomial distribution error structure was assumed. Many studies *(*37*,* 38*)* have demonstrated the inappropriateness of conventional linear regression in modeling discrete, non-negative, rare events such as traffic accident occurrence, due to the non-linear relationship with traffic volume and road length. GLIM has the advantage of overcoming these shortcomings associated with conventional linear regression. The regression analyses were performed by use of the GenStat 7.2 software package.

The model form is as follows:

$$\hat{E}(Y) = e^{a_0} \times L^{a_1} \times AADT^{a_2} \tag{15}$$

where:

$\hat{E}$ (Y) = predicted accident frequency (in 5-year period);
L = segment length (km);
AADT = average annual daily traffic (vehicles per day);
a_0, a_1, a_2 = model parameters.

The model parameters and the indicators for the model significance are listed in Table 7. The reported indicators are the t-ratio for the model parameters, the κ value (the negative binomial parameter), the scaled deviance (SD), the Pearson χ^2 statistic and the log likelihood. The formulation of the SD (for a negative binomial distribution) and of the Pearson χ^2 statistic are shown in equations 16 and 17. For a well-fitted model, both the scaled deviance and the Pearson χ^2 should be significant compared with the critical value obtained from the χ^2 distribution for the given degrees of freedom and level of confidence.

$$SD = 2\sum_{i=1}^{n}\left[yi\ln(\frac{yi}{\hat{E}(yi)}) - (yi+k)\ln(\frac{yi+k}{\hat{E}(yi)+k}) \right] \tag{16}$$

where:

SD = scaled deviance;
y_i = observed number of accidents in the segment i;
$\hat{E}(y_i)$ = predicted number of accidents in the segment i;
k = the negative binomial parameter.

$$Pearson\ \chi^2 = \sum_{i=1}^{n} \frac{\left[yi - \hat{E}(yi)\right]^2}{Var(yi)} \qquad (17)$$

where:

$Var(y_i)$ = variance of the observed accidents.

TABLE 7 Model Parameters and Indicators for Model Goodness of Fit

Df	Parameter	Estimate	t-ratio	$t_{0.10,27}$	k	SD	Pearson χ^2	$\chi^2_{0.10,27}$	Log Likelihood
27	a_0	-5.861	-2.48	1.70	3.56	34.09	26.44	36.74	-18.84
	a_1	0.601	1.85						
	a_2	0.747	2.59						

These measures indicate that the prediction model has a relatively good fit and the values that are calculated for the t-ratios for all independent variables are significant.

The collision estimates were then subjected to an Empirical Bayes refinement technique (EB) to correct for regression-to-mean bias and to obtain a better estimate of the expected accident frequency (see Table 8).

EB was produced as follows:

$$EB = \left(\frac{\hat{E}(Y)}{k + \hat{E}(Y)}\right) \times (k + count) \qquad (18)$$

where:

EB = empirical Bayes estimate of the accident frequency;
count = observed accident frequency.

TABLE 8 Accident History and EB Estimates

Section	Road Name	Length (km)	AADT (veh/day)	Observed Injury Accidents	Model Predicted Accidents	EB Estimate
1	SP 4II	3.463	4100	5	3.01	3.92
2	SP 4II	2.782	4100	2	2.64	2.37
3	SP 4II	0.639	4100	3	1.09	1.54
4	SP 4II	2.740	5200	5	3.13	4.00
5	SP 57	4.505	1800	5	1.91	2.99
6	SP 57	1.399	1800	0	0.94	0.75
7	SP 69II	3.084	5500	1	3.50	2.26
8	SP 69II	6.425	1800	5	2.36	3.41
9	SP 69II	3.115	1800	3	1.53	1.97
10	SP 69II	5.328	600	1	0.93	0.94
11	SP 69II	1.038	600	0	0.35	0.32
12	SP 69II	1.456	600	0	0.43	0.38
13	SP94	5.628	900	2	1.30	1.49
14	SP94	7.636	900	0	1.56	1.09
15	SP94	1.817	900	1	0.66	0.71
16	SP94	2.988	900	0	0.89	0.71
17	SP104	6.854	1200	1	1.81	1.54
18	SP104	2.409	1200	0	0.97	0.76
19	SP104	2.220	1200	0	0.92	0.73
20	SP104	2.874	2900	0	2.08	1.31
21	SP104	2.094	2900	4	1.72	2.46
22	SP231	3.887	3500	1	2.87	2.04
23	SC4	1.175	4500	2	1.69	1.79
24	SC4	1.814	4000	0	2.01	1.28
25	SC4	2.165	4000	1	2.23	1.76
26	SC4	1.146	4000	0	1.52	1.07
27	SP 28II	1.260	1100	2	0.61	0.82
28	SP 28II	3.347	1100	2	1.10	1.32
29	SP 28II	2.580	1100	1	0.94	0.96
30	SP 28II	5.273	1100	1	1.45	1.32

Comparison of SI Scores and EB Estimates

To test the procedure, comparisons were carried out between SI scores and EB safety estimates (see Table 9). The correlation between SI values and EB safety estimates is highly significant ($t = 9.64$, p-value < 0.001), with 77% of the variation in the estimated number of accidents explained by the SI value (see Figure 1). This means that the relationship between EB estimates and SI scores had less than 0.1% chance of occurring by accident. Comparisons between SI/L scores and EB/L safety estimates give similar results. The correlation between EB/L safety estimates and SI/L values is highly significant ($t = 9.05$, p-value < 0.001), with 75% of the variation in the estimated number of accidents per kilometer explained by the SI/L value.

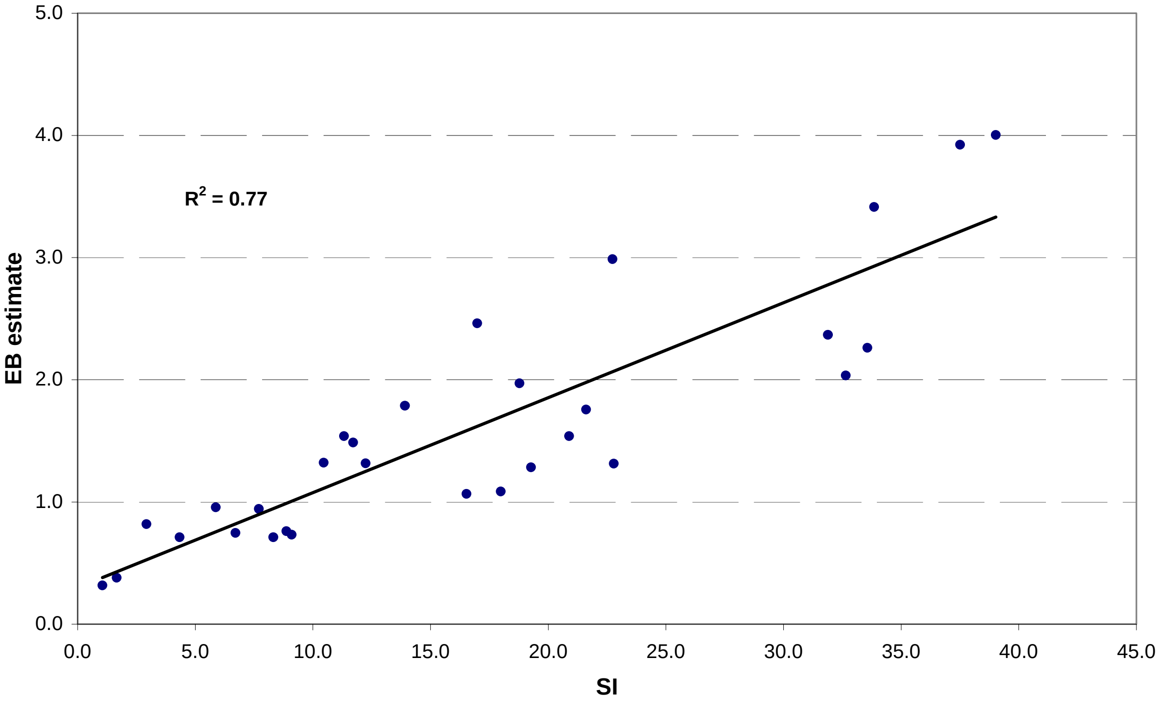

FIGURE 1 Correlation between SI scores and EB safety estimates.

To test the procedure further, a comparison was made of the rankings obtained by the SI and by the EB technique. Indeed, the main target of the procedure is to define management priorities with respect to road safety. Spearman's rank-correlation was used to determine the level of agreement between the rankings obtained using the two techniques. The Spearman's rank-correlation coefficient is a measure of association between the rankings of two variables measured on N individuals. To calculate the Spearman's rank-correlation coefficient, it is necessary to segment the data sets and then rank the paired data sets in ascending or descending order. The Spearman's rank-correlation coefficient is often used as a non-parametric alternative to a traditional coefficient of correlation and can be applied under general conditions. An advantage of the method is that when testing for correlation between two sets of data, it is not necessary to make assumptions about the nature of the populations sampled. The correlation coefficient is calculated from the two vectors of ranks for the samples: let {Xi; i=1...n} and {Yi; i=1...n} be the vectors of ranks for sample 1 and sample 2 respectively, then it results:

$$\rho_s = 1 - \frac{6\times\sum_{i=1}^{n} d_i^{\,2}}{n\times(n^2-1)} \tag{19}$$

where:

ρ_s = Spearman's rank-correlation coefficient;
d_i = differences between ranks;
n = number of paired sets.

TABLE 9 Comparison Between Ranking Criteria

Section	Exposure Factor	Accident Frequency Factor	Accident Severity Factor	SI	EB Estimate	SI Rank	EB Rank	SI/L	EB/L	SI/L Rank	EB/L Rank
1	14.20	2.68	0.98	37.50	3.92	2	2	10.83	1.13	7	5
2	11.41	2.89	0.97	31.89	2.37	6	6	11.46	0.85	5	7
3	2.62	4.92	0.88	11.32	1.54	19	13	17.72	2.41	1	1
4	14.25	3.33	0.82	39.02	4.00	1	1	14.24	1.46	3	3
5	8.11	4.63	0.61	22.73	2.99	8	4	5.05	0.66	15	11
6	2.52	4.66	0.57	6.71	0.75	25	25	4.79	0.53	16	14
7	16.96	1.67	1.19	33.57	2.26	4	7	10.88	0.73	6	9
8	11.57	2.10	1.39	33.86	3.41	3	3	5.27	0.53	14	15
9	5.61	2.50	1.34	18.78	1.97	12	9	6.03	0.63	13	13
10	3.20	2.02	1.20	7.71	0.94	24	22	1.45	0.18	28	29
11	0.62	3.55	0.47	1.05	0.32	30	30	1.01	0.30	30	23
12	0.87	2.15	0.89	1.66	0.38	29	29	1.14	0.26	29	25
13	5.07	3.84	0.60	11.71	1.49	18	14	2.08	0.26	26	24
14	6.87	3.70	0.71	17.99	1.09	13	19	2.36	0.14	23	30
15	1.63	5.27	0.50	4.33	0.71	27	27	2.39	0.39	22	19
16	2.69	4.62	0.67	8.32	0.71	23	28	2.78	0.24	21	27
17	8.22	1.85	1.37	20.89	1.54	10	12	3.05	0.22	20	28
18	2.89	2.25	1.36	8.88	0.76	22	24	3.68	0.32	18	22
19	2.66	2.42	1.41	9.09	0.73	21	26	4.10	0.33	17	21
20	8.33	1.86	1.47	22.78	1.31	7	17	7.93	0.46	12	17
21	6.07	2.43	1.15	16.98	2.46	14	5	8.11	1.18	11	4
22	13.60	5.02	0.48	32.65	2.04	5	8	8.40	0.52	10	16
23	5.29	2.73	0.97	13.91	1.79	16	10	11.84	1.52	4	2
24	7.26	2.89	0.92	19.27	1.28	11	18	10.62	0.71	8	10
25	8.66	1.94	1.29	21.61	1.76	9	11	9.98	0.81	9	8
26	4.58	4.45	0.81	16.53	1.07	15	20	14.43	0.93	2	6
27	1.39	3.18	0.67	2.93	0.82	28	23	2.33	0.65	24	12
28	3.68	3.68	0.90	12.25	1.32	17	16	3.66	0.39	19	18
29	2.84	3.97	0.52	5.87	0.96	26	21	2.27	0.37	25	20
30	5.80	3.21	0.56	10.46	1.32	20	15	1.98	0.25	27	26
							ρ_s = 0.87				**ρ_s = 0.87**
							T = 9.54				**T = 9.15**
							p-value < 0.001				**p-value < 0.001**

A score of 1.0 represents perfect correlation and a score of zero indicates no correlation. The t-approximation for this statistic, T, is valid for samples of size 8 upwards, and is calculated by:

$$T = \rho_s \times \sqrt{\frac{n-2}{1-\rho_s^{\;2}}} \tag{20}$$

It has approximately a t-distribution with n-2 degrees of freedom, and can be used for a test of the null hypothesis of independence between samples.

The results from the Spearman's rank-correlation analysis (see Table 8) provide further validation for the SI indicating that the ranking from the SI and the EB estimate agree at the 99.9% level of significance with a correlation coefficient of 0.87. The same level of agreement is obtained if rankings from SI/L and from EB/L are compared.

CONCLUSIONS

The procedure integrates two different approaches, one based on design consistency evaluation and the other on safety inspections, and makes it possible to effectively address a wide variety of safety issues.

Validation of the safety evaluation procedure was carried out by comparing the results with the accident EB estimates. The SI was assessed in 30 segments of two-lane rural highways in Italy. An accident predictive model was calibrated for the same road network and the EB refinement technique was used to obtain a better estimate of the expected accident frequency. The correlation between SI values and EB safety estimates is highly significant ($t = 9.64$, $p\text{-value} < 0.001$), with 77% of the variation in the estimated number of accidents explained by the SI value. This means that the relationship between EB estimates and SI scores had less than 0.1% chance of occurring by accident. Comparisons between SI/L scores and EB/L safety estimates give similar results. Moreover, Spearman’s rank-correlation was used to determine the level of agreement between the rankings obtained by the two techniques. The results from the Spearman's rank-correlation analysis provide further validation for the SI indicating that the ranking from the SI and the EB estimate agree at the 99.9% level of significance with a correlation coefficient of 0.87. The same level of agreement is obtained if rankings from SI/L and from EB/L are compared. These results show that ranking of segments gives comparable results in terms of SI or accident frequency.

The SI can be assessed whether accident data are available or not. If accident data are available and are of good quality, the SI can be effectively used in conjunction with accident frequency as ranking criteria. If accident data are not available or are unreliable, the SI can be used as a proxy for accident data and becomes the only ranking criteria. The SI has two, main applications. High-risk segments, where safety measures that can reduce accident frequency and/or severity already exist, can be identified and ranked by the SI score. Specific safety issues, that give more contribution to unsafety, are pointed out by the Accident Frequency factor and the Accident Severity factor in order to give indications regarding more appropriate mass-action programs.

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