Cost–Effectiveness Evaluation of Different Safety Interventions Strategies on Two-Lane Rural Highways

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ABSTRACT

Nowadays, an essential part of any Safety Management System is the network screening, that is the identification of sites where the greatest cost-effectiveness of safety measures is expected. In rehabilitation and reconstruction projects, geometric improvements of existing roads represent higher costs with respect to other safety improvements related to pavement, markings, sign, safety barrier or other low cost interventions.

For the safety evaluation of a road section, in a previous study carried out by the authors, a Safety Index (SI) was 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 showed the advantage of applicability on two lane local rural roads where crash data are either not available or statistically not significant.

Due to the significant correlation found between SI values and EB safety estimates, in this paper a methodological approach using the SI to evaluate the effectiveness of alternative investment in delivering specified levels of safety under constant budget is presented. Specifically, the cost-effectiveness ratio of alternative investments related to different intervention strategies was evaluated in terms of SI variation (ΔSI) and cost during a defined cycle life. For an allocated budget, the ΔSIs obtained using different intervention strategies can be related to an expected accident reduction and therefore they can be effectively used as ranking criteria into a Safety Management System.

In the case of unlimited available budget, the research shows that Geometry strategy (G) is still the more effective one in a level terrain scenario, while in different terrain conditions the Roadside strategy (R) is to be preferred, emphasizing the highly cost-effectiveness ratio at any budget and/or terrain characteristics.

INTRODUCTION

Nowadays, an essential part of any Safety Management System is the network screening, that is the identification of sites where the greatest cost-effectiveness of the safety measures is expected. Traditionally, Safety Performance of existing roads are raised by targeting investments to the road sections with the highest crash density or the highest potential for crash reduction. Moreover, due to budget constrains, also analyses have to be carry out to establish the circumstance under which a road intervention is cost-effective by examining cost versus safety trade-offs for a series of alternative projects.

Local two-lane rural roads, i.e. typology of highways investigated, are the part of the National road network that provides access to land and towns. In Italy and in other European countries local rural roads are characterized by a low-medium traffic flow (1.000÷6.000 veich./day) and short-distance journeys (5÷20 km). On local rural roads, low traffic volume results in a relatively low number of crashes. Therefore, for these class of roads traditional approach to network screening based on crash data can raise concerns both due to the few crash data occurring due to low traffic and to the deficiency of reliable data on road crashes.

As a result of these considerations, in the European Project "Identification of Hazard Locations and Ranking of Measures to Improve Safety on Local Rural Roads" (Italian acronym IASP), a new surrogate measure of safety (Safety Index, SI) was defined to supplement crash investigation studies for the safety evaluation of two-lane rural highways based on design consistency models and on Road Safety Inspections (RSIs) (*1- 4*).

The methodology was validated using five-year data on two lane local rural roads in Italy to test correlation between the empirical Bayesian (EB) crash frequency estimates and SI estimates. Due to the significant correlation found between SI values and EB safety estimates *(5, 6*), in this paper a methodological approach using the SI to evaluate the effectiveness of alternative investment in delivering specified levels of safety under constant budget is presented. Specifically, the cost-effectiveness ratio of alternative investments related to different intervention strategies was evaluated in terms of SI variation (ΔSI) and costs during a defined cycle life. For an allocated budget, the ΔSIs obtained using different intervention strategies can be related to an expected crash reduction and therefore they can be effectively used as ranking criteria into a safety management system.

With the aim to highlight the usefulness of the procedure, referring to different terrain and budget scenarios, a sensitivity analysis was carried out to identify threshold values in the cost-effectiveness ratio of alternative strategies based on (a) expensive structural intervention such as that ones on geometry and cross section, (b) intervention on road side and accesses, (c) maintenance routine intervention such as pavement maintenance and signs.

BACKGROUND

Recently, the European Directive 2008/96/CE requires the establishment and implementation of procedures relating to *road safety impact assessments*, *road safety audits*, *management of road network safety* and *safety inspections* by the Member States which are obliged to implement suitable measures until 2010 *(7)*.

Even though the Directive will be applied to roads which are part of the trans-European road network, however, Member States are invited to apply the provisions of this Directive, as a set of good practices, to national road transport infrastructure, not included in the trans-European road network.

In the Directive RSI is defined as “an ordinary periodical verification of the characteristics and defects that require maintenance work for reasons of safety” *(7)*. RSIs are recognized as a valuable and proactive tool and are becoming an accepted practice in many agencies around the world *(8 - 14)*. Recent researches carried out in Italy *(13 - 15)*, in EU *(14)* and in British Columbia (*9*) have shown that road safety impact assessment based on RSIs can be highly cost-effective. However, due to the subjective nature of the process, standard RSIs may give rise to disagreements which limit their effectiveness.

In IASP project an operative and quantitative RSI process which uses procedures and criteria for identifying and ranking safety issues was defined and guidelines were edited *(15)*.

Checklists used in RSIs procedure are filled in for both directions of the road, with a step of 200 m using procedures and criteria for identifying and ranking safety issues purposely set up in which features 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 significant contribution to road safety of Design Consistency Evaluation was the other stage in SI calculation. It was evaluated through an overall Safety Module defining three design classes: poor, fair, good combining the following three safety criteria *(16, 17, 18, 19)*:

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.

Specifically, in the SI procedure the Safety Module was used to check the consistency of curves, while, with regard to the safety concerns related to long or short tangents, design standards checks were carried out according to the criteria defined in the Italian Standards.

The reader who is interested in a more detailed discussion of dealing with Design consistency Evaluation should consult *(16,17,18)*.

The SI is formulated by combining the three components of risk: the exposure of road users to road hazards, the probability of a vehicle being involved in a collision and the resulting consequences should a crash occur *(6)*. The systematic and replicable procedure of the SI makes it possible to effectively address a wide variety of safety issues.

Specifically, the *Exposure Factor* (EF) measures the exposure of road users to road hazards, depending by the length of the segment under consideration (L) and by the average annual daily traffic (AADT).

The *Accident Severity Factor* (AS) is intended as a measure of the ratio between the number of severe crashes (injury or fatal) and the total number of crashes and relates to operating speed and roadside hazard.

The *Accident Frequency Factor* (AF) depends on the safety features of the segment, which are assessed by two methodologies: RSIs and Design Consistency Evaluations and Standards Check:

- RSIs relate to the main safety issues that may be consistently present along two-lane rural roads (Accesses, Cross section, Delineation, Markings, Signs, Pavement, Roadside, Sight distance). Identification and ranking are carried out by the way of a visual survey of the road using appropriate checklist *(3, 4, 15).*

- Design Consistency and Standards Check refer to the safety evaluation of the horizontal alignment based on the Safety Criteria proposed by Lamm *(16, 17, 18, 19)* for curves and on design standards for tangents.

Table 1 reports the related crashes and relative increase in safety risk that were considered in the SI for the different safety issues composing the model. The reader who is interested in a more detailed discussion of dealing with SI should consult reference (*6).*

Safety Issue	**Related Accidents**	**relative increase in accident risk (%)**
Geometry	Run off the road Partially (50%): Head-on, sideswipe	700
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	200
Sight distance	All	50
Signs	All	20

Table 1 – Safety Effects of the Issues

The distinctive characteristic of the procedure is that the SI can be assessed whether crash data are available or not. If crash data are available and are of good quality, the SI can be effectively used in conjunction with collision frequency as ranking criteria. Viceversa if crash data are not available or are unreliable, the SI can be used as surrogate measure of safety (a proxy for crash data) and becomes the only ranking criteria. High-risk segments, where safety measures can reduce crash frequency and/or severity,, can be identified and ranked by the SI score. Moreover, specific safety issues, that give more contribution to unsafety, are pointed out by the procedure in order to give indications regarding more appropriate mass-action programs and particular interventions as it will be shown in the following paragraphs. Finally, the proposed approach is a preventive one, i.e. the safety improvements can be carried out in an hazard location before the crash happens.

Within the validation of the procedure, comparisons were carried out between SI scores and actual crash on a sample of road segments. Specifically, using crash data collected for a five years period of accident history on the road sample, a crash prediction model using the segment length and the AADT as explanatory variables, was developed *(6).* The crash estimates subjected to an empirical Bayes technique (EB) allows the refinement to correct for regression-to-mean bias and to obtain a better estimate of the expected accident frequency. In order to test the procedure, comparisons were carried out between SI scores and EB safety estimates. The correlation between SI/L values and EB/L estimates resulted highly significant (R2=0.75, 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).

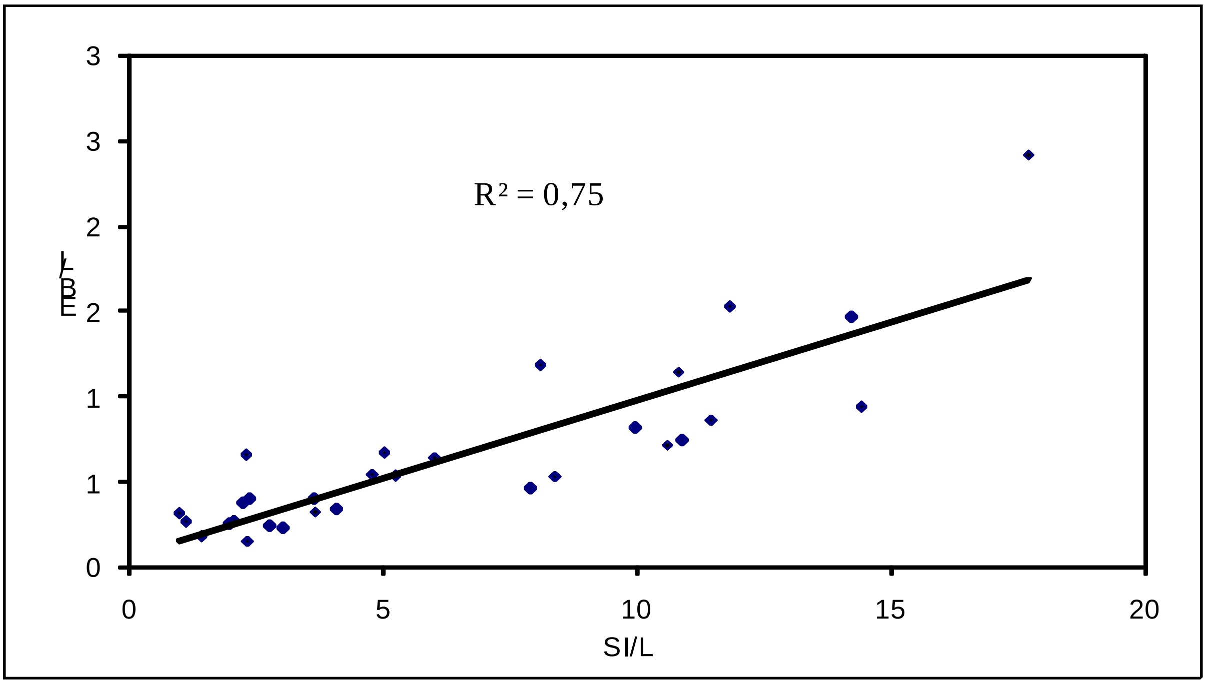

Figure 1 - SI/L scores versus EB/L estimates

To test the procedure further, a comparison of the rankings obtained by the SI and by the EB technique was made. 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.

The results highlight that increasing in SI scores determine an increase in crash expectancy.

COST-EFFECTIVENESS EVALUATION USING THE SAFETY INDEX

For an allocated budget, using different intervention strategies a reduction of SI values (ΔSI) can be obtained and related to an expected reduction in the number of crashes. Therefore, cost-effectiveness ratio of alternative investments connected to different intervention strategies were evaluated in terms of SI variation (ΔSI) and related cost into a cycle life analysis.

In this context, it is important to specify that the SI of a road segment can increase its value during the life cycle due to a worsening of road conditions (e. g. pavement, marking, sign, delineation) if adequate maintenance works are not applied.

Starting from this assumption the effectiveness of each intervention was evaluated using the following formula

$$\Delta SI_m = SI_0 - SI_m$$

where:

- ΔSI_m is the benefit during the life cycle related to the road segment due to the intervention *m*;

– SI_0 represents the Safety Index during the life cycle related to the road segment if no intervention or maintenance works are applied;

– SI_m represents the Safety Index during the life cycle related to the road segment due to intervention *m* and related maintenance works.

With the aim to highlight the usefulness of the procedure, referring to different terrain and budget scenarios, analyses were carried out to identify cost-effectiveness of different alternative strategies.

A local rural road, two km long, with an operating speed of 90 km/h and an AADT of 4000 vehicles per day, was assumed as example. Alternatively three different terrain scenarios were considered (Level (L), Rolling (R) and Mountainous terrain (M)) and the analysis were carried out for a Life Cycle Cost (LCC) of 20 years.

The worst state for each factor composing the SI was assumed as base condition to which the highest value of SI can be associated to the road segment (SI=408.4). It was assumed that the different interventions are able to improve the related safety issue (geometric design, accesses, cross section, roadside, delineation, markings, signs and pavement) from the worst to the best state during the LCC also considering maintenance works and costs.

Table 2 shows the estimated costs related to different typologies of treatment for 2 kilometres of road segment. Costs for the application of Geometry modifications of the road are related with the terrain characteristics (Level, Rolling, Mountainous). In the table frequency refers to the need of maintenance works to be carried out to maintain the efficiency of the treatment.

Treatment	**Frequency (years)**	**Cost (€)**		
		Level Terr.	**Rolling Terr.**	**Mountainous Terr.**
Geometric Design	-	626,250	970,650	1,315,050
Accesses	-	90,000	90,000	90,000
Cross Section	-	374,890	1,076,810	2,172,330
Roadside	-	640,000	640,000	640,000
Delineation	5	79,909	79,909	79,909
Markings	3	31,920	31,920	31,920
Signs	7	14,400	14,400	14,400
Pavement	7	974,700	974,700	974,700

Table 2: Cost estimated for each typology of intervention (euro)

In the context of road management usually combination of different typologies of intervention can be considered based on budget constrains and opportunity of complementary works. For the present study three alternative strategies as combination of the previous categories, were analyzed:

- *Geometry (G),* characterized by expensive structural intervention on geometry design and cross section;

- *Road Side (R)*, characterized by intervention on road side hazard and accesses (number decrease or reorganization);
- *Pavement (P)*, characterized by routine intervention such as pavement maintenance, marking, signs and delineation.

It is evident from Figure 2 that, without budget implication, the best solution is represented by the geometry strategy (the reader has to consider that the reference condition SI_0 is a alignment with “poor” geometric design and consistency).

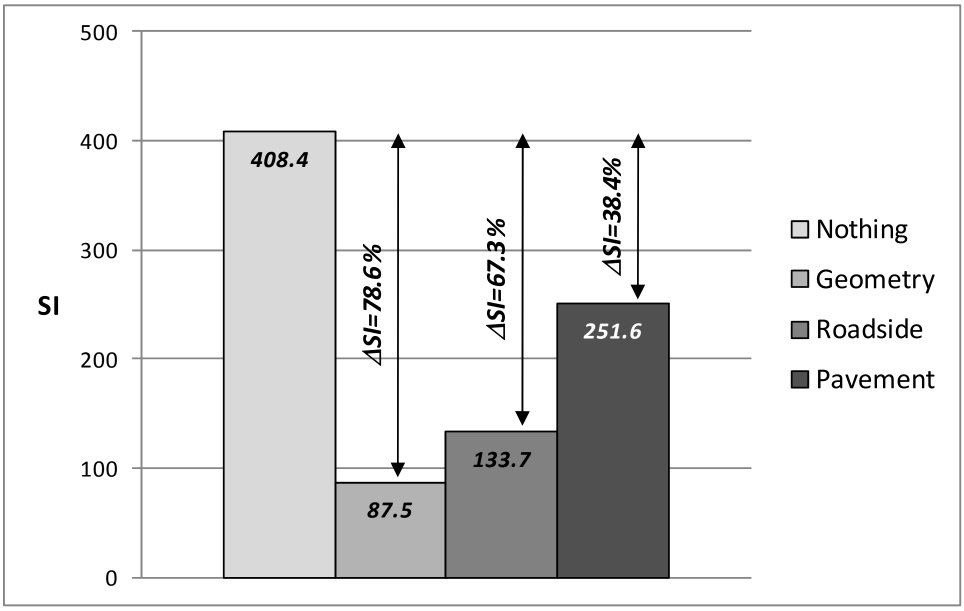

Figure 2 Effectiveness (ΔSI%) of the selected strategies with unlimited budget

However, with the aim to support the road agency in decision making process, it is necessary to define a procedure taking into account both benefits and cost.

In the present work, in order to highlight the capability of SI to evaluate the efficiency of each strategy (*G*, *R*, *P*) respect to its cost and in function of the available budget (*B*), Cost/Benefit ratio and SI_{FACTOR} were computed:

$$Cost/Benefit = SI_S \cdot C_S$$

$$SI_{FACTOR} = \frac{SI_S \cdot C_S}{B}$$

where

SI_S : value of SI after the implementation of strategy S;

C_S : life cycle cost for the implementation of strategy S;

B : allocated budget ($B \geq C_S$).

Cost/benefit ratio is the traditional factor to evaluate and to compare the effectiveness of different alternatives with different benefits and costs. SI_{FACTOR} was defined to take into account also the available budget and to compare alternatives based on different budget allocations.

Referring to the benefit/cost ratio, Figure 3 emphasizes the effectiveness of the three strategies if different costs are considered in the analysis (i.e. available budget is unlimited), showing as geometry strategy (G) is still the more effective one in a level terrain scenario, while in different terrain conditions the roadside strategy (R) is to be preferred.

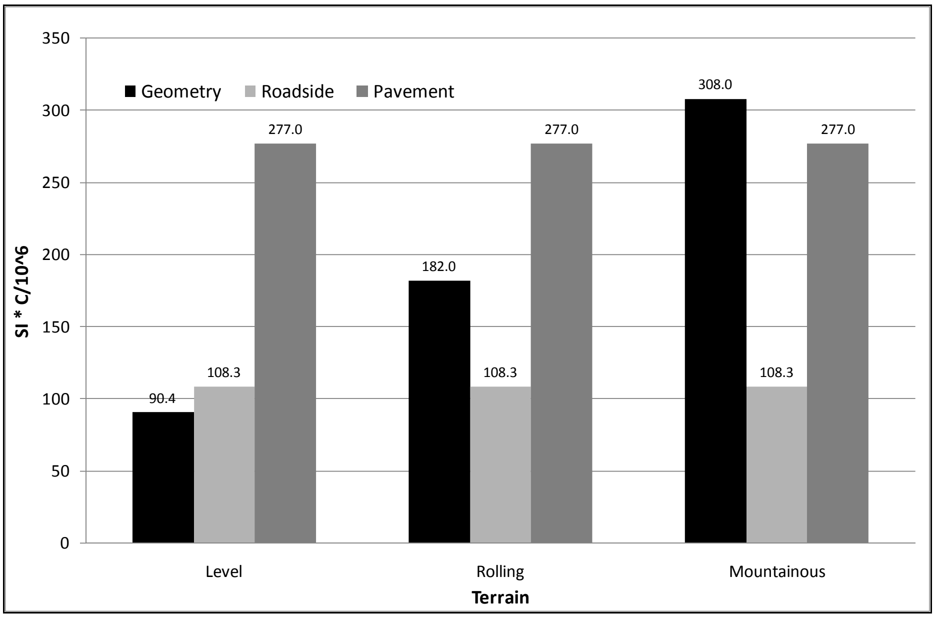

Figure 3: Cost/benefit of the selected strategies

For different terrain scenarios Figure 4, Figure 5 and Figure 6 report the SI_{FACTOR} of each strategy when the budget decreases till to the 20% of the needed one (% Budget=100%) for the implementation of the more expensive strategy applied to the full road segment (% Segm.=100%). While the budget decreases, the percentage of the road segment interested by maintenance activities can also decrease due to insufficient budget allocation.

Budget		Geometry				Roadside				Pavement				Min(SIxC/B)	Opt. Strat.
%	€	% Segm.	SI	Cost (€)	SIxC/B	% Segm.	SI	Cost (€)	SIxC/B	% Segm.	SI	Cost (€)	SIxC/B		
100%	1,100,929	100%	87.5	1,033,060	82.1	100%	133.7	810,000	98.4	100%	251.6	1,100,929	251.6	82.1	G
90%	990,836	90%	119.6	929,754	112.2	100%	133.7	810,000	109.3	90%	267.3	990,836	267.3	109.3	R
80%	880,743	80%	151.7	826,448	142.4	100%	133.7	810,000	123.0	80%	283.0	880,743	283.0	123.0	R
70%	770,650	70%	183.8	723,142	172.5	90%	161.2	729,000	152.5	70%	298.6	770,650	298.6	152.5	R
60%	660,557	60%	215.9	619,836	202.6	80%	188.6	648,000	185.1	60%	314.3	660,557	314.3	185.1	R
50%	550,464	50%	248.0	516,530	232.7	60%	243.6	486,000	215.1	50%	330.0	550,464	330.0	215.1	R
40%	440,371	40%	280.1	413,224	262.8	50%	271.1	405,000	249.3	40%	345.7	440,371	345.7	249.3	R
30%	330,279	30%	312.2	309,918	292.9	40%	298.5	324,000	292.9	30%	361.4	330,279	361.4	292.9	R-G
20%	220,186	20%	344.2	206,612	323.0	20%	353.5	162,000	260.1	20%	377.1	220,186	377.1	260.1	R

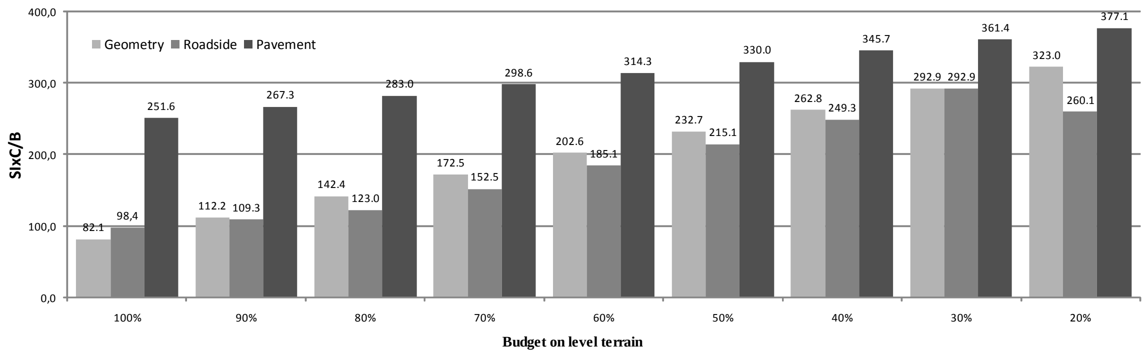

Figure 4 **Strategies selection on the level terrain scenario**

Budget		Geometry				Roadside				Pavement				Min(SIxC/B)	Opt. Strat.
%	€	% Segm.	SI	Cost (€)	SIxC/B	% Segm.	SI	Cost (€)	SIxC/B	% Segm.	SI	Cost (€)	SIxC/B		
100%	2,079,380	100%	87.5	2,079,380	87.5	100%	133.7	810,000	52.1	100%	251.6	1,100,929	133.2	52.1	R
90%	1,871,442	90%	119.6	1,871,442	119.6	100%	133.7	810,000	57.9	100%	251.6	1,100,929	148.0	57.9	R
80%	1,663,504	80%	151.7	1,663,504	151.7	100%	133.7	810,000	65.1	100%	251.6	1,100,929	166.5	65.1	R
70%	1,455,566	70%	183.8	1,455,566	183.8	100%	133.7	810,000	74.4	100%	251.6	1,100,929	190.3	74.4	R
60%	1,247,628	60%	215.9	1,247,628	215.9	100%	133.7	810,000	86.8	100%	251.6	1,100,929	222.0	86.8	R
50%	1,039,690	50%	248.0	1,039,690	248.0	100%	133.7	810,000	104.2	90%	267.3	990,836	254.7	104.2	R
40%	831,752	40%	280.1	831,752	280.1	100%	133.7	810,000	130.2	70%	298.6	770,650	276.7	130.2	R
30%	623,814	30%	312.2	623,814	312.2	70%	216.1	567,000	196.4	50%	330.0	550,464	291.2	196.4	R
20%	415,876	20%	344.2	415,876	344.2	50%	271.1	405,000	264.0	30%	361.4	330,279	287.0	264.0	R

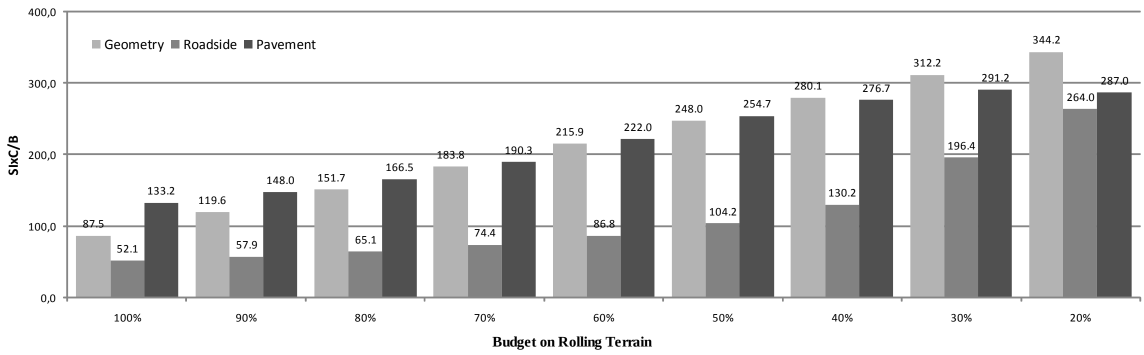

Figure 5 **Strategies selection on the rolling terrain scenario**

Budget		Geometry				Roadside				Pavement				Min(SIxC/B)	Opt. Strat.
%	€	% Segm.	SI	Cost (€)	SIxC/B	% Segm.	SI	Cost (€)	SIxC/B	% Segm.	SI	Cost (€)	SIxC/B		
100%	3,519,300	100%	87.5	3,519,300	87.5	100%	133.7	810,000	30.8	100%	251.6	1,100,929	78.7	30.8	R
90%	3,167,370	90%	119.6	3,167,370	119.6	100%	133.7	810,000	34.2	100%	251.6	1,100,929	87.5	34.2	R
80%	2,815,440	80%	151.7	2,815,440	151.7	100%	133.7	810,000	38.5	100%	251.6	1,100,929	98.4	38.5	R
70%	2,463,510	70%	183.8	2,463,510	183.8	100%	133.7	810,000	44.0	100%	251.6	1,100,929	112.4	44.0	R
60%	2,111,580	60%	215.9	2,111,580	215.9	100%	133.7	810,000	51.3	100%	251.6	1,100,929	131.2	51.3	R
50%	1,759,650	50%	248.0	1,759,650	248.0	100%	133.7	810,000	61.5	100%	251.6	1,100,929	157.4	61.5	R
40%	1,407,720	40%	280.1	1,407,720	280.1	100%	133.7	810,000	76.9	100%	251.6	1,100,929	196.8	76.9	R
30%	1,055,790	30%	312.2	1,055,790	312.2	100%	133.7	810,000	102.6	90%	267.3	990,836	250.8	102.6	R
20%	703,860	20%	344.2	703,860	344.2	80%	188.6	648,000	173.7	60%	314.3	660,557	295.0	173.7	R

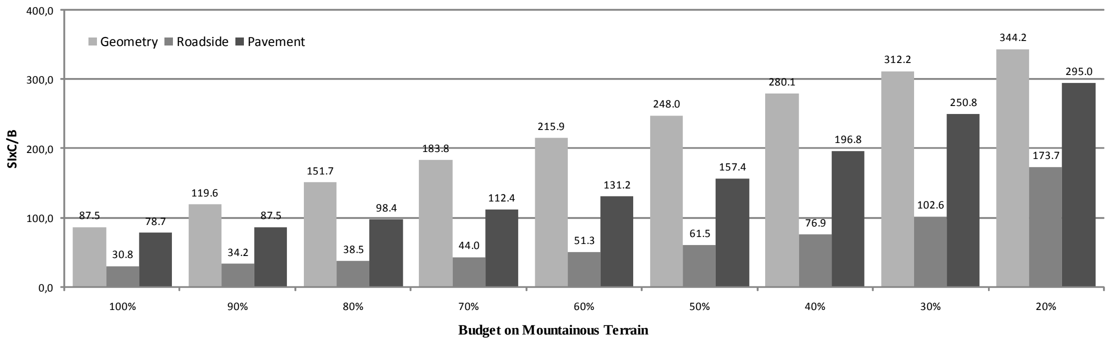

Figure 6 **Strategies selection on the mountainous terrain scenario**

Analysis of results for the three scenarios are summarized in Figure 7, highlighting as Roadside (R) strategy is always the preferred one in terms of cost-effectiveness ratio at any budget and/or terrain characteristics with the exception of the availability of the whole budget and level terrain while, as previously defined in the unlimited budget hypothesis, Geometry (G) strategy is preferred. Specifically in the Figure 7 strategies prioritization is reported for each budget and terrain scenario, ranking three different combination of interventions:

- *Geometry, Roadside, Pavement* (GRP);
- *Roadside, Geometry, Pavement* (RGP);
- *Roadside, Pavement, Geometry* (RPG).

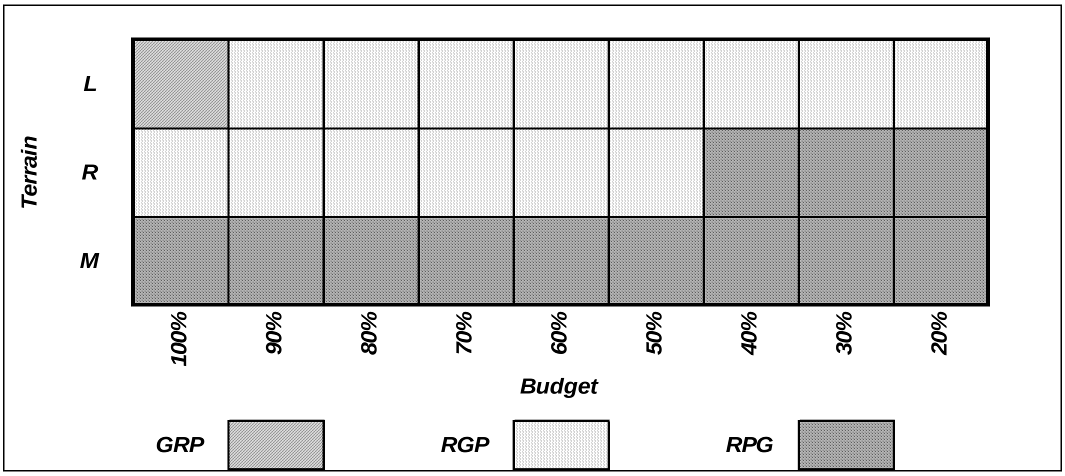

Figure 7 **Strategies prioritization under different budget and terrain scenarios**

Introducing budget limitation, cost-effectiveness of the selected strategies changes in function of the external condition confirming as roadside hazard mitigation and accesses management present the highest values. When budget decreases and terrain is quite unlevelled geometry strategy became less efficient with respect to other safety improvements. Obviously, in the real world, the best results can be obtained with a combination of different strategies based on actual safety deficiencies in the road system and available budget.

CONCLUSIONS

For the safety management of local two lane rural roads, where the network screening based on the observed crashes can be affected by the lack of quality and insufficient number of collision data, alternative analyses have to be carry out to establish the circumstance under which a given road intervention is cost-effective by examining cost versus safety trade-offs for a series of alternative projects.

For road agencies having the problem of budget constrains in the selection of rehabilitation and reconstruction projects, the proposed procedure is very effective because it is able to cover the whole process from the identification of safety deficiencies, with a proactive approach (RSIs and Design Consistency), to the evaluation of the intervention alternative with the best benefit/cost ratio within the available budget.

In the case of unlimited available budget, the research shows that Geometry strategy (G) is still the more effective one in a level terrain scenario, while in different terrain conditions the Roadside strategy (R) is to be preferred, emphasizing the highly cost-effectiveness ratio at any budget and/or terrain characteristics.

Presented results can’t be immediately transferred to real world applications that have to consider the actual road conditions and intervention costs. Anyway, the study gives useful information about the cost/benefit efficiency of alternative intervention strategies and results highlights that the use of SI as surrogate measure of Safety allowed specific strategies prioritization for each budget and terrain scenario, ranking different combination of interventions.

For the aim of the study, it was assumed that each road segment can be optimized, without considering what happens to other ones. However, in network management, optimization has to be based on the balancing improvements among various segments in order to address maximum benefit with the same funds. An in progress research is referring to the use of SI in this issue.

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