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Original Research Paper

# Prioritization methodology for roadside and guardrail improvement: Quantitative calculation of safety level and optimization of resources allocation

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## HIGHLIGHTS

- Four categories of defects/elements that affect roadsides risk were detected.
- A method for analysing and planning maintenance of safety barriers was proposed.
- A cost-benefit analysis permitted to prioritize possible rehabilitation works.

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## ABSTRACT

The attention to road safety-related issues has grown fast in recent decades. The experience gained with these themes reveals the importance of considering these aspects in the resource allocation process for roadside and guardrail improvement, which is a complex process often involves conflicting objectives. This work consists on defining an innovative methodology, with the objective of calculating and analysing a numerical risk factor of a road. The method considers geometry, accident rate, traffic of the examined road and four categories of elements/defects where the resources can be allocated to improve the road safety (safety barriers, discrete obstacles, continuous obstacles, and water drainage). The analysis allows the assessment of the hazard index, which could be used in decision-making processes. A case study is presented to analyse roadsides of a 995 km long road network, using the cost-benefit analysis, and to prioritize possible rehabilitation work. The results highlighted that it is suitable to intervene on roads belonging to higher classes of risk, where it is possible to maximize the benefit in terms of safety as consequence of rehabilitation works (i.e., new barrier installation, removal and new barrier installation, and new terminal installation). The proposed method is quantitative; therefore, it avoids providing weak and far from reliable results; moreover, it guarantees a broad vision for the problem, giving a useful tool for road management body.

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## 1. Introduction

Roadsides, if not properly designed, would be a dangerous factor for vehicles which may run off the roadway. In fact, within these spaces discrete elements (e.g., trees, walls, buildings, etc.) or continuous obstacles (e.g., worn-out and broken roadside safety barriers, unprotected drainage channels, etc.) (AASHTO, 2011) could increase the consequences of a road exit of vehicles, as confirmed by Elvik (1995). Over the years, the problem of safety has led to the development of various strategies to reduce the number of deaths related to the local environment and road. Possible strategies to improve the safety of existing roadsides are: replacing or removing the obstacles; changing the roadside elements and protecting the obstacles with restraint devices (Elvik et al., 2004).

The European Directive 2008/96/EC (European Commission, 2008) on the safety management of road infrastructure establishes management procedures ensuring safety of road network. It encouraged the definition and use of road infrastructure safety management (RISM) on roads included in the trans-European transport network (TEN-T). Particularly, it set up guidelines for providing and maintaining safety barriers and obstacle-free roadsides. Furthermore, the European Union (EU) promoted the project Improving Roadside Design to Forgive Human Errors (IRDES) (Nitsche et al., 2011). It provided guidelines for the design of margins, which reduce the consequences of an excursion from the road. Another study focused on the roadside protection needs was the SAVeRS project (La Torre et al., 2016), which developed a practical and readily understandable method to select the most appropriate solution about restraint systems, specifically considering road and traffic conditions.

In Italy, the Legislative Decree 35/11 (Parlamento Italiano, 2011) advised to implement a RISM on four levels: network analysis; inspection; classification; and intervention. A RISM procedure permits to identify, plan, and schedule all the necessary works.

In the Italian territory, the often-complex orography limits the adoption of clear areas, largely used at international level (AASHTO, 2011), and implies the use of safety barriers. These devices safely redirect and prevent vehicles from crossing or leaving the roadway and engaging the roadside. Under these conditions, safety barriers also are obstacles. In order to properly perform their function, they should be well designed and maintained; otherwise, they can cause other unsafe conditions, as confirmed in the literature.

More than 50 years ago, Stonex (1960) has already revealed that the departure of the vehicle from the roadway causes 35% of fatal accidents. He also identified several factors (e.g., the presence of obstacles close to the road edge, such as steep slopes, deep ditches, and inadequate terminals of safety barriers) that increase the severity of the consequences in case of incident.

Several studies analysed the frequency and severity of accidents involving a collision with a specific “object” on the roadside (Gagne, 2008; Good et al., 1987; Kennedy, 1997; Lee and Mannering, 1999; Neuman et al., 2003; Ray, 1999; Road and Traffic Authority NSW, 2004; Viner, 1995; Wolford and Sicking, 1997). The risk analyses carried out on this type of accident show the severity of the crash depends essentially on the object hit by the vehicle, while its probability depends on other aspects that characterize the road (Cafiso et al., 2010). Indeed, the accident may be related to the width of lanes and shoulder, the horizontal curvature, and the access density (Abdel-Aty and Radwan, 2000; Bellini and Ristori, 2011; Cafiso et al., 2008; Pardillo and Llamas, 2003; Zhang and Ivan, 2005). As a consequence of the risk analysis, a method should provide a strategy for addressing the resources available and providing the necessary maintenance work (Jorgensen, 1966). At this scope, Pigman and Agent (1991) suggested that the management bodies keep an inventory of the existing barriers before allocating the funds. Usually, the optimization of the management of funds is based on objective functions, which maximize and/or minimize the considered decision variables (Bierman et al., 1997; Hillier and Lieberman, 2005; Lambert et al., 2003). For example, an adopted solution is to optimize safety benefits by maximizing the monetary value of avoided accidents (Mishra, 2013; Miccoli et al., 2014a). Cost-benefit analysis could be efficiently used to evaluate safety and economic impacts of barriers management, to compare the impact of different solutions, and/or to assess specific performances (Miccoli et al., 2014b; Loprencipe et al., 2017). Detailed finite element analyses may be performed to evaluate the acceptability of different barrier alternatives (Bonin et al., 2006, 2009).

As regard as benefit-to-cost and cost-effectiveness analysis methods, in recent decades, various agencies and research bodies made big efforts to identify and implement new procedures. Among the most important contributions, it should be noted that since 1970s and through 2010s, various methods were proposed in the context of the National Cooperative Highway Research Program (NCHRP). With reference to the aims of this paper, procedures for the safety performance evaluation of highway appurtenances can be already found in the NCHRP Report 230 (Michie, 1981); afterwards, NCHRP Report 350 focused on testing and in-service evaluation of roadside safety systems (Ross et al., 1993). A very innovative approach, which suggested some of the analyses developed in the present paper, came with NCHRP Report 492, that proposed the use of Monte Carlo simulation techniques (Mak and Sicking, 2003). Again, other procedures have been presented in the subsequent documents (Dixon et al., 2008; Mak, 2010).

On the basis of the above presented state of knowledge, the aim of this study is to provide a tool for analysing and planning maintenance of safety barriers using a cost-benefit approach. It derives from a railway methodology used to evaluate the service condition of bridges (RFI and CNIM, 2002). The proposed method considers the hazards associated with road stretches and their cost of rehabilitation (Miccoli et al., 2015), then it gives priority to those measures which maximize the gain in terms of overall safety of the road network. The intervention typologies considered in the proposed method take into account the experiences available in the literature. Therefore, they consider the inherent hazards, the hazard density (extension and/or abundance), the accident rate of the road stretch, the traffic volume, and the design consistency of the road. In this study, the method has been developed for rural roads with single carriageway, but also it could be adapted to other types of roads. It applies to road sections with both steel and concrete safety barriers installed or planned, and it focuses on the conditions which require a new barrier design.

**Table 1 – Priority factor values of considered elements/defects.**

| Category | Code | $K_1$ |
|---|---|---|
| Safety barriers | SB | 1.0 |
| Discrete obstacles | DO | 0.8 |
| Continuous obstacles | CO | 0.8 |
| Water drainage | WD | 0.6 |

## 2. Materials and methods

The experimental model developed within the "Project Domus" (RFI and CNIM, 2002), sponsored by R.F.I. (Italian Railway Network) S.P.A. and C.N.I.M. (Italian National Committee for Maintenance) permits to evaluate the danger of railway bridges. In this research, following the same approach, it has been considered to determine the hazard profile of a roadside.

A numeric index *I* (hazard index) quantifies the overall risk assessment of a roadside: the more is the *I* value, the lower is the safety provided by the roadside along the infrastructure stretch. Therefore, the value of *I* depends on the dangerousness of the roadside $V_{Pj}$, which is calculated for each *j* km of the road. $V_{Pj}$ considers general characteristics of the road (i.e., design consistency, accident rate, and level of traffic), and all *n* elements which are along the sides according to Eq. (1)

$$V_{Pj} = \sum_{i=1}^{n} B_i \times K_{1i} \times K_{2i} \times K_3 \times K_4 \times K_5 \tag{1}$$

where $V_{Pj}$ is the risk factor of the examined distance (km), $B_i$ is the base value associated to each of *n* elements *i* which are along the roadside. It considers the category to which the element *i* belongs, $K_{1i}$ is the priority factor of the category to which the element *i* belongs, $K_{2i}$ is the extent factor of each of *n* elements *i* which are along the roadside. It takes into account the quantity or numerosity of *i* elements, $K_3$ is the accidents factor of examined road. It considers the accident rate of the examined road, $K_4$ is the traffic factor of the examined road, derived from the Average Annual Daily Traffic (AADT), $K_5$ is the design consistency factor of examined road calculated according to the Lamm criteria (Lamm et al., 1988).

The calculation of $V_{Pj}$ for all *m* km of the road permits to assess its hazard index *I* (Eq. (2)

$$I = R / R_r \times 100 \tag{2}$$

where *R* is the sum of the risk factor of *m* 1 km long stretches which compose the road given by Eq. (3)

$$R = \sum_{j=1}^{m} V_{Pj} \tag{3}$$

$R_r$ is the reference value of the risk factor given by Eq. (4)

$$R_r = mV_{Pref} \tag{4}$$

where $V_{Pref}$ is equal to the sum of all allowable maximum values for all possible roadside elements (RFI and CNIM, 2002). Therefore, *I* depends on the maximum values of $K_{1i}$, $K_{2i}$, $K_3$, $K_4$ and $K_5$, and its values range value between 0 and 1, as in Eq. (2).

The attribution of possible values of $K_{1i}$, $K_{2i}$, and $B_i$ required interviewing technicians from different backgrounds, experts in the fields of road, geotechnics, hydraulics, and human health. Ten road engineers, ten geotechnics engineers, nine hydraulics engineers, and eight traumatologists were interviewed. The authors defined for each variable the maximum and minimum value according to the model developed within the "Project Domus" (RFI and CNIM, 2002), then each technician respected this range while attributing the values. Finally, the geometric mean has been used to aggregate individual judgements and the values set out below.

According to the Italian standards about roadside composition (Ministero delle Infrastrutture e dei Trasporti, 2001), the method analyses all possible lateral obstacles and road defects which could interfere with the safe circulation (Pardillo-Mayora et al., 2010).

**Table 2 – Base values of considered elements/defects.**

| Description | Code | $B_i$ |
|---|---|---|
| Safety barriers: absent but imposed by the reference standard | SB1 | 4 |
| Safety barriers: present but inadequate | SB2 | 3 |
| Singular point (transition or terminal) | SB3 | 3 |
| Tree within 3 m from the carriageway | DO1a | 4 |
| Tree within 8 m from the carriageway (but more than 3 m) | DO1b | 3 |
| Light, power, telephone pole, phone box, bus shelter within 3 m from the carriageway | DO2a | 3 |
| Light, power, sign, telephone pole, phone box, bus shelter within 8 m from the carriageway (but more than 3 m) | DO2b | 2 |
| Bridges, tunnels, abutments and other structures | DO3 | 4 |
| Fence, hedge, drainage of adjacent road | DO4 | 2 |
| Building within 10 m from the carriageway | DO5 | 4 |
| Embankment cliff ($20^\circ < i \le 40^\circ$, 1 m $< h <$ 3 m) | CO1a | 2 |
| Embankment cliff ($40^\circ < i \le 60^\circ$, 1 m $< h <$ 3 m) | CO1b | 3 |
| Embankment cliff ($i > 60^\circ$, 1 m $< h <$ 3 m) | CO1c | 4 |
| Embankment cliff ($20^\circ < i \le 40^\circ$, $h >$ 3 m) | CO1d | 3 |
| Embankment cliff ($40^\circ < i \le 60^\circ$, $h >$ 3 m) | CO1e | 4 |
| Embankment cliff ($i > 60^\circ$, $h >$ 3 m) | CO1f | 4 |
| Cutting slope ($20^\circ < i \le 40^\circ$, $h >$ 1 m) | CO2a | 2 |
| Cutting slope ($40^\circ < i \le 60^\circ$, $h >$ 1 m) | CO2b | 3 |
| Cutting slope ($i > 60^\circ$, $h >$ 1 m) | CO2c | 4 |
| Rock cliff | CO3 | 4 |
| Ditch, watertable, drainage | CO4 | 3 |
| Surface water body (e.g., river, lake, sea) | CO5 | 3 |
| Railway or other transport infrastructure parallel to the road | CO6 | 4 |
| Total inefficiency (e.g., obstruction, rupture…) | WD1 | 1 |
| Absent but necessary system | WD2 | 1 |
| Inadequate system | WD3 | 1 |

Note: geometrical criteria listed in column "description" refer to Fig. 1. Embankments and cuttings within 1 m are not considered as continuous obstacles.

**Table 3 – Extent factor values $K_2$ for continuous elements/defects.**

| Level of severity | Condition | $K_2$ |
|---|---|---|
| Low | Element present along less than 250 m | 1 |
| Moderate | Element present along more than 250 m and less than 500 m | 2 |
| High | Element present along more than 500 m and less than 750 m | 3 |
| Extreme | Element present along more than 750 m | 4 |

The authors identified 4 categories of elements/defects: safety barriers (SB), discrete, rigid obstacles (DO), continuous obstacles (CO), and water drainage (WD). Table 1 lists their priority factors $K_1$.

Each element/defect which belongs to a category listed in Table 1 has its base value $B_i$ which satisfies Eq. (5). Table 2 lists the defined base values $B_i$.

$$1 \leq B_i \leq 4 \tag{5}$$

Table 3 lists the $K_2$ coefficients: they are related to the extension of continuous elements/defects listed in Table 2. All possible conditions refer to the examined 1 km long road stretch.

For discrete (and rigid) obstacles, it is more correct to evaluate their extension based on number of times they are present along the examined kilometre. This analysis should consider the geometrical characteristics of the overall evaluated network. The interviewed technicians allowed the compilation of the catalogue listed in Table 4.

As regard as the occurred accidents on the examined road, the authors took into account only lateral road excursions (run-off-road accidents): they occur when a vehicle leaves the side of the carriageway during its movement and collide with a roadside element (for example, head-on collisions and rear-end collisions are not considered in the study).

Both statistical geo-referenced occurred accidents (ISTAT, 2016) and the AADT contribute to the calculation of the accident rate $T_i$ (Eq. (6))

$$T_i = \frac{10^6 N_i}{365 l_i \sum_t^Y \mathrm{AADT}_{i,t}} \tag{6}$$

where $N_i$ is the number of occurred accidents on the examined stretch $i$, $l_i$ is the length of the examined stretch (1 km), $\mathrm{AADT}_{i,t}$ is the average annual daily traffic of the examined stretch during the year $t$ of analysis, $Y$ is the number of years of observation.

All obtained $T_i$ values contribute to the classification of the accident rate of the overall road, and therefore allow the assessment of the coefficient $K_4$. The authors proposed three levels of road accident rate. The procedure to classify the road accident rate complies with Italian road safety guidelines published by the Ministry of Infrastructures (Ministero delle infrastrutture e dei trasporti, 2012a). The method consists of calculation of $T^*_{\mathrm{inf}}$ and $T^*_{\mathrm{sup}}$ respectively defined by Eqs. (7) and (8)

$$T^*_{\mathrm{inf}} = T_{\mathrm{m}} - P\sqrt{\frac{T_{\mathrm{m}}}{M_i}} - \frac{1}{2M_i} \tag{7}$$

$$T^*_{\mathrm{sup}} = T_{\mathrm{m}} + P\sqrt{\frac{T_{\mathrm{m}}}{M_i}} + \frac{1}{2M_i} \tag{8}$$

where $T^*_{\mathrm{inf}}$ and $T^*_{\mathrm{sup}}$ are respectively the lower and upper reference value of traffic for the examined road branch, $P$ is the probability constant of the Poisson's distribution (Scozzafava, 1995), in this study, $P$ is assumed equal to 1.645, with 90% confidence level, $T_{\mathrm{m}}$ is the average accident rate of the itinerary, calculated as in Eq. (9)

$$T_m = \frac{10^6 \sum N_i}{365 \sum_i \sum_t l_i \mathrm{AADT}_{i,t}} \tag{9}$$

**Table 4 – Extent factor values $K_2$ for discrete elements/defects (into 1 km of road).**

| Elements/defects | Number of elements/defects | Level of risk | $K_2$ |
|---|---|---|---|
| Unique point | 1–2 | Low | 1 |
| | 3–4 | Moderate | 2 |
| | 5–6 | High | 3 |
| | >6 | Extreme | 4 |
| Portals, tunnel's entrance | 1 | Low | 1 |
| | 2 | Moderate | 2 |
| | 3 | High | 3 |
| | >3 | Extreme | 4 |
| Drainage system on the road | 1–2 | Low | 1 |
| | 3–5 | Moderate | 2 |
| | 6–8 | High | 3 |
| | >8 | Extreme | 4 |
| Building | 1 | Low | 1 |
| | 2 | Moderate | 2 |
| | 3 | High | 3 |
| | 4 | Extreme | 4 |

**Table 5 – Values of road accident rate $K_3$.**

| Condition | Road accident rate | $K_3$ |
|---|---|---|
| $T_i < T^*_{\mathrm{inf}}$ | Low | 1 |
| $T^*_{\mathrm{inf}} < T_i < T^*_{\mathrm{sup}}$ | Medium | 2 |
| $T_i > T^*_{\mathrm{sup}}$ | High | 3 |

**Table 6 – Values of traffic factor $K_4$.**

| Condition | Traffic level | $K_4$ |
|---|---|---|
| $\mathrm{AADT} < \mathrm{AADT}_{\mathrm{m}} - \sigma$ | Low | 1 |
| $\mathrm{AADT}_{\mathrm{m}} - \sigma < \mathrm{AADT} < \mathrm{AADT}_{\mathrm{m}} + \sigma$ | Medium | 2 |
| $\mathrm{AADT} > \mathrm{AADT}_{\mathrm{m}} + \sigma$ | High | 3 |

**Table 7 – Design consistency criteria.**

| Code | Design consistency criteria (km/h) | Operating speed consistency criteria (km/h) | Driving dynamics consistency criteria |
|---|---|---|---|
| A | $\lvert V_{85} - V_p \rvert \leq 10$ | $\lvert V_{85,k} - V_{85,k+1} \rvert \leq 10$ | $f_{td} - f_{tr} \geq 0$ |
| B | $10 < \lvert V_{85} - V_p \rvert \leq 20$ | $10 < \lvert V_{85,k} - V_{85,k+1} \rvert \leq 20$ | $-0.02 \leq f_{td} - f_{tr} < 0$ |
| C | $\lvert V_{85} - V_p \rvert > 20$ | $\lvert V_{85,k} - V_{85,k+1} \rvert > 20$ | $f_{td} - f_{tr} < -0.02$ |

**Table 8 – Values of geometric design consistency $K_5$.**

| Condition | $K_5$ |
|---|---|
| ≥2 codes C | 3 |
| Maximum 1 code C or no code A | 2 |
| ≥1 code A and no code C | 1 |

Note: criteria listed in column "condition" refer to codes listed in Table 7.

$M_{i,t}$ is the traffic moment of stretch $i$ during the examined year $t$ according to Eq. (10)

$$M_{i,t} = 365 l_i \sum_t^Y AADT_{i,t} \qquad (10)$$

Table 5 lists the values of road accident rate $K_3$.

Under the exposed hypotheses, the proposed road accident rate criteria are reliable only in presence of homogeneous stretches. In this analysis, road branches are considered homogeneous if they have uniform/homogeneous attributes related to accident rate, geometrical characteristics, composition of cross section, design and limit speed.

As regard as the level of traffic, AADT is the parameter to be considered. The authors considered the average annual daily traffic on the overall considered network ($AADT_m$) and its standard deviation $\sigma$. These values, compared with the AADT of the examined road, give the coefficient $K_4$ listed in Table 6.

As regard as the inconsistency of geometric design, the Lamm's theory (Lamm et al., 1988) has been considered. It consists of three quantitative safety criteria (Table 7):

- The first one refers to the design consistency and compares the design speed $V_p$ and the operating speed $V_{85}$, defined as 85% speed or the speed at or below which 85% of the vehicles are travelling.
- The second one refers to the operating speed consistency. It compares $V_{85}$ of two successive geometric elements ($k$ and $k+1$).
- The third one refers to the consistency in driving dynamics. It compares the assumed side friction $f_{td}$ (considered during the design process) and the demanded side friction $f_{tr}$, which depends on $V_{85}$, the planimetric radius, and the transversal slope.

The criteria proposed by Lamm et al. should be applied to each geometrical element of the examined kilometre. At the end of the analysis, it is possible to assign the value of $K_5$, as listed in Table 8.

Compared to other available models, the proposed one allows considering many and more detailed infrastructure features, achieved by means of the factors $K_1$, …, $K_5$, in order to define road and roadside conditions. In particular, if considering the iRAP (international road assessment programme) approach and the derived methods (U.S.RAP, EuroRAP, AUSRAP, …), they are generally based on general variables like: crash types and seriousness, distance and type of roadside obstacles, speed and traffic level of the road, and so on (iRAP, 2014). On the contrary, the presented method permits to take into account more technical conditions, and to assign quantitative evaluation of their relevance respect to safety performance. In the authors' opinion, deeper analyses can be provided in this way, so allowing better addressing the proposed safety actions.

A complete analysis of the roadside condition also requires the definition of $I$ values classes. At this purpose, the authors considered six probabilistic classes of risk level, as usually done for road and airport risk assessment (Bonin et al., 2017; Di Mascio and Loprencipe, 2016; Loprencipe et al., 2015; Moretti et al., 2017a; b; c; Moretti et al., 2018). The definition of ranges for each class requires a significant number of monitored roads to know the typical values of $I$ under real conditions. When a sample of real cases is not available, the method can also be used by calibrating the index by means of data coming from simulations. In this case, a Monte Carlo simulation permitted to characterize $I$ selecting a random sample from each distribution. Simulations (Mooney, 1997) were conducted obtaining the mean value and the standard deviation that allow to calculate the limit value of the index $I$ for each classes of risk.

In these simulations, all possible cases for all components are allocated by random generators, by assigning a random value to the coefficients $K_2$, $K_3$, $K_4$ and $K_5$. For each simulation,

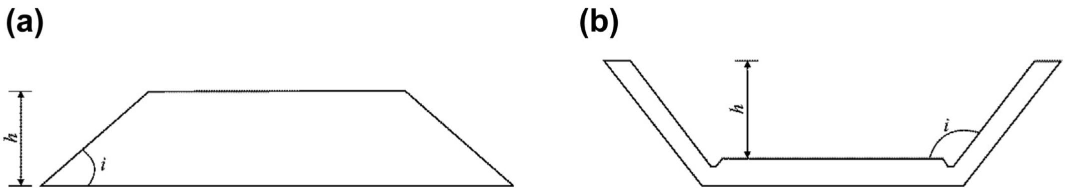

**Fig. 1 – Geometrical characteristics. (a) Embankment. (b) Trench cross section.**

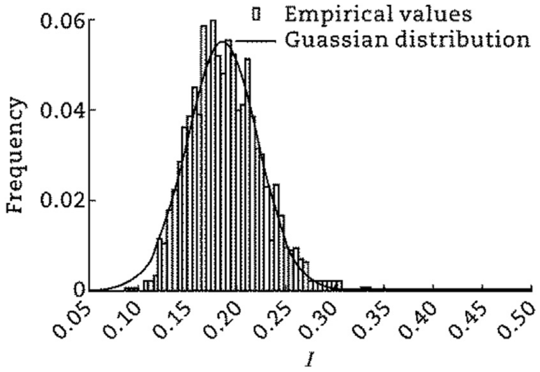

**Fig. 2 – Comparison between empirical simulated results and the Gaussian distribution.**

a defectiveness is achieved for the roadside condition (considering priority, extension, accident, etc.)

Data obtained from the simulations can be effectively represented by relative frequency distribution, by means of histograms or cumulative frequency distribution curve.

Fig. 2 shows the results from 2000 simulations, and it compares the empirical and analytical frequency distributions: the former derives from the Monte Carlo simulation, the latter represents the Gaussian curve (Scozzafava, 1995).

Fig. 2 shows a good closeness between the two distributions. Therefore, the results of the performed simulations allowed defining six classes of risk $I$ and calculating their relative probabilities having the average $\mu$ and the standard deviation $\sigma$ of the normal distribution probability (Table 9).

Finally, a cost-benefit analysis (Lambert et al., 2003) has been carried out to prioritize possible safety actions (i.e., rehabilitation works).

For the cost analysis, the rehabilitation costs for each road V could be evaluated using the lists of road prices currently adopted for the Italian National road network (ANAS, 2017). Table 10 lists the considered unit prices.

Each type of work listed in Table 10 implies a cost $C_i$; therefore, the overall cost necessary for the rehabilitation of each $V$ is (Eq. (11))

$$C_R = \sum_i C_i \tag{11}$$

For the benefit analysis, the average density of accidents costs (ADAC) has been calculated before ($\text{ADAC}_b$) and after ($\text{ADAC}_a$) the intervention according to Eq. (12).

$$\text{ADAC} = \text{AACA} / L \tag{12}$$

where AACA is the average annual cost of accidents according to Eq. (13)

$$\text{AACA} = N_d \times C_d + N_{sI} \times C_{sI} + N_{mI} \times C_{mI} \tag{13}$$

where $N_d$, $N_{sI}$ and $N_{mI}$ are respectively the number of deaths, serious injuries and minor injuries; $C_d$, $C_{sI}$ and $C_{mI}$ are respectively the average cost of deaths, serious injuries and minor injuries (Ministero delle Infrastrutture e dei Trasporti, 2012b), $L$ is the length of $V$.

The calculation of $\text{ADAC}_b$ requires statistical data, while the calculation of $\text{ADAC}_a$ needs for prediction of the effects of the safety actions on the human health (Harwood et al., 2003). Data obtained from the literature led to the conditions listed in Table 11 (Elvik et al., 2004; Gitelman and Hakkert, 2014; ISTAT, 2017).

Only the accidents (and their consequences) related to lateral barriers should be considered to calculate $\text{ADAC}_a$ (for the “after” period); this assumption assumes that all elements/defects that specifically concern the roadsides have been managed and solved.

The benefits assumed in consequence of the rehabilitation works listed in Table 10 shall apply in proportion to the length of the rehabilitated road.

For each examined $V$, the benefit $B_R$ (Eq. (14))

$$B_R = \text{ADAC}_a - \text{ADAC}_b \tag{14}$$

Permits to quantify the annual benefit in terms of social costs when all necessary safety actions have been carried out.

Finally, the authors wrote a program to evaluate the economic benefits of the safety actions and compare them with the related rehabilitation costs. The procedure allows the identification of the most effective solutions which satisfy Eq. (15)

$$\max = \sum_i (B_i / C_i) \tag{15}$$

Having Eq. (16)

$$C_R = \sum_i C_i \le M \tag{16}$$

where $M$ is the available budget.

Each solution implies the rehabilitation of the entire length of the roads $V$, which ensure the whole highest benefit-cost

**Table 9 – Classes of risk.**

| Class | Risk level | Criterion | Probability | $I$ | |
|---|---|---|---|---|---|
| | | | | Minimum (%) | Maximum (%) |
| I | Not relevant risk | $I < \mu$ - $5\sigma$ | 2.87E-10 | < | 0.43 |
| II | Low risk | $\mu$ - $5\sigma < I < \mu$ - $4\sigma$ | 3.14E-05 | 0.43 | 4.04 |
| III | Average risk | $\mu$ - $4\sigma < I < \mu$ - $3\sigma$ | 1.32E-03 | 4.04 | 7.65 |
| IV | High risk | $\mu$ - $3\sigma < I < \mu$ - $2\sigma$ | 2.14E-02 | 7.65 | 11.26 |
| V | Very high risk | $\mu$ - $2\sigma < I < \mu$ - $\sigma$ | 1.36E-01 | 11.26 | 14.87 |
| VI | Critical risk | $I > \mu$ - $\sigma$ | 8.41E-01 | > | 14.87 |

**Table 10 – Unit prices for rehabilitation works.**

| Type of work | Cost |
|---|---|
| New barrier installation | 34.20 €/m |
| Removal and new barrier installation | 41.85 €/m |
| New terminal installation | 78.17 €/each |

**Table 11 – Percentage reduction of ADAC after safety actions.**

| Type of work | $(ADAC_a - ADAC_b)/ADAC_b$ (%) |
|---|---|
| New barrier installation | −20 |
| Removal and new barrier installation | −15 |
| New terminal installation | −5 |

**Table 12 – Classification of functional, geometric and accident factors of examined road.**

| Stretch | $R_1$ | $R_2$ | $R_3$ | $R_4$ | $R_5$ |
|---|---|---|---|---|---|
| | 0–1 km | 1–2 km | 2–3 km | 3–4 km | 4–5 km |
| $K_3$ | 3 | 3 | 3 | 3 | 3 |
| $K_4$ | 3 | 3 | 3 | 3 | 3 |
| $K_5$ | 1 | 2 | 1 | 2 | 1 |

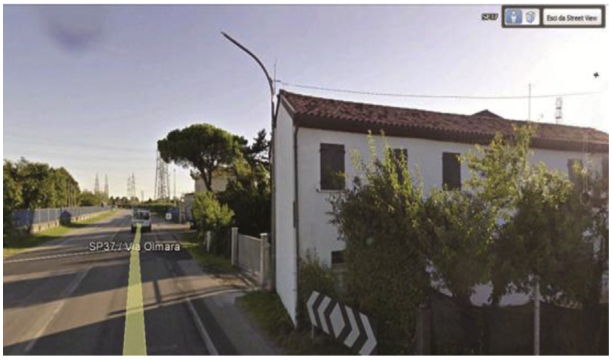

Fig. 3 – Presence of defects SB1 (safety barriers: absent but imposed by the reference standard), and DO5 (building within 10 m from the carriageway).

ratio (B/C). This approach is justified by a common and shared reason; it is not appropriate to rehabilitate single-road sections, because the user would not have uniform safety conditions, as required by the organisation for economic co-operation and development (OECD, 2003).

## 3. Case study

The proposed methodology has been applied on an Italian secondary road network with single carriageway, whose total length is 995 km with a maximum allowable speed of 90 km/h. All the roads are managed by the same road agency and have the same classification. Geometrical and functional data were considered to classify the branches both by traffic (volume, composition) and accident rate.

Fig. 4 – Presence of defects SB2 (present but inadequate safety barriers), SB3 (singular point of safety barriers), and CO4 (ditch).

**Table 13 – Classification of elements/defects recognized in Figs. 3 and 4.**

| Source | Fig. 3 | | Fig. 4 | | |
|---|---|---|---|---|---|
| | SB1 | DO5 | SB2 | SB3 | CO4 |
| Coefficient $K_1$ | 1 | 0.8 | 1 | 1 | 0.8 |
| Base value $B_i$ | 4 | 4 | 3 | 3 | 3 |
| Coefficient $K_2$ | 4 | 4 | 1 | 2 | 3 |

**Table 14 – *I* values for examined stretches.**

| Stretch | *I* (%) | Class |
|---|---|---|
| $R_1$ | 1.67 | II |
| $R_2$ | 2.51 | II |
| $R_3$ | 15.67 | VI |
| $R_4$ | 9.82 | IV |
| $R_5$ | 6.17 | III |

For the sake of brevity, the authors present the calculation of *I* for a single road (Code S37) belonging to the network. It is 5 km long; therefore, it was divided in five 1 km long stretches whose functional, geometric, and accident factors are listed in Table 12.

The roadside analysis carried out by the authors consisted of the detailed surveying on the road branch, with the aim to recognize the defects/elements that characterize each section. As examples, Figs. 3 and 4 represent two critical conditions, whose elements/defects are classified in Table 13.

Fig. 5 shows the planimetric representation of all the discrete or continuous elements/defects found along the examined road.

The proposed method gave the *I* values listed in Table 14 for the stretches of S37.

The hazard index *I* calculated for the overall road is 7.17% (class III). The obtained results highlight and quantify severe risk conditions for several stretches, particularly for $R_3$, which has the highest value of *I*, equal to 15.67%. The analytical results confirm the qualitative analysis that can be derived from Fig. 5. In fact, $R_3$ has several discrete and continuous obstacles, and furthermore, it lacks safety barriers.

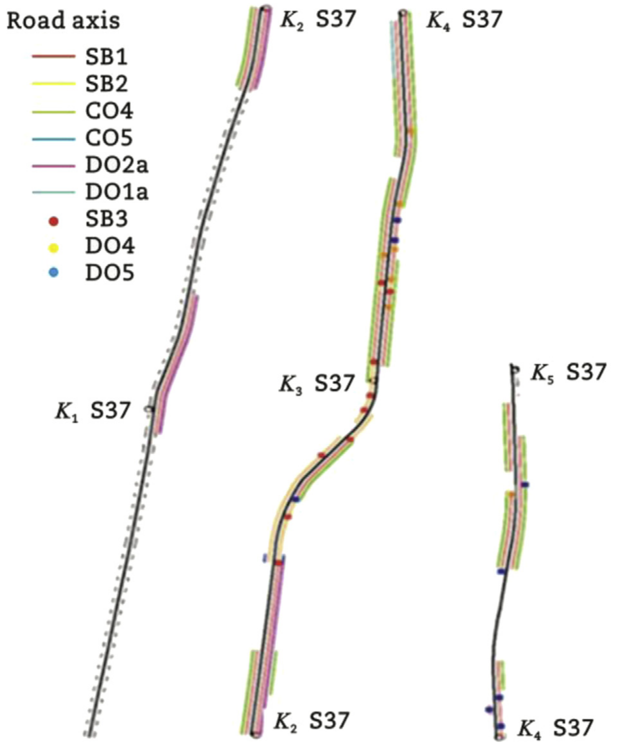

**Fig. 5 – Layout of examined road ($K_n$ is the end of the $n$-th kilometre of the road S37).**

The same calculation has been carried out on the other branches of the whole road network, composed of 61 roads, whose length and *I* values are listed in Table 15. The roads are identified with the alpha-numerical code S*r*, where *r* ranges from 1 to 61.

The examined network has 534 km of roads, which belong to class II, 336 km of class III, 103 km of class IV and 22 km of class V. Each kilometre of the 61 roads is considered as a homogeneous branch. The considered safety actions consist in the installation or implementation of passive safety devices (longitudinal road barriers, terminals, restraint systems).

The cost-benefit analysis as decision aid for fund allocation involved the roads listed in Table 16. Fig. 6 represents for each examined road its cost and benefit per kilometre. It is interesting to observe that the single values of cost per kilometre are very close to the average one, equal to 43.4 €/km. This result demonstrates that the safety barrier conditions of the overall network are uniform, therefore about the same investment per kilometre should be undertaken to improve them. On the other hand, the safety level is not the same on the network, as confirmed by the trend of benefit per kilometre in Fig. 6, which is very irregular. Particularly, 16 roads do not have monetary benefit as consequence of barriers rehabilitation: this result complies with the approach used in benefits estimation. Indeed, the method considers only the safety (as the preservation of human health): B/C ratio is equal to 0 if the road did not have accidents or if it did have accidents without consequence on people (deaths, serious and minor injuries).

The cost and benefit amounts represented in Fig. 6 point out the need to closely deepen the any possible B/C ratio varying investment strategies. Fig. 7 shows the curves of cumulated costs and benefits related to rehabilitation of the first twenty roads in order of decreasing B/C ratio.

For the first 15 roads, the whole cumulated cost of rehabilitation is lower than their benefit regarding human health (safety). This result is confirmed by Fig. 8, which presents the opposite trends of B/C ratio and rehabilitated kilometres of the network. The horizontal dotted line represents the B/C ratio equal to 1: it overlaps with B/C ratio curve between the 15th and 16th roads. Therefore, in the examined network, only the rehabilitation of 180 km ensures a B/C ratio higher than 1 with a total investment of more than 7.7 M€.

While considering that B/C ratio more than 1 is essential condition to rehabilitate safety barriers, because it implies that the potential saving from the reduced/avoided damages is more than the real cost of the rehabilitation works, the very significant amount requires a closer examination. Indeed, each road management body should keep spending within imposed budget limits, with the aim of maximizing the valuable resources.

Three cost-benefit analyses have been carried out considering three budgets available to the road agency for managing the 61 roads listed in Table 16:

- the first one (A1) has a budget of 1000 k€.
- the second one (A2) has a budget of 2000 k€.
- the third one (A3) has a budget of 4000 k€.

The results listed in Table 16 highlight that it is suitable to intervene on roads belonging to higher classes of *I*; therefore, they have the higher B/C ratio. In fact, the most advantageous works involve roads which hold the first positions on the chart in Table 15: the analysis does not involve road within the 18th place at the time when the analysis has been carried out.

The economic analysis is therefore consistent with the risk analysis. Some disagreements (e.g., the results of A1 analysis do not involve roads with class V, which are in Table 15) are related to the different approaches of the risk and economic analyses. The evaluation of index *I* depends on the AADT, the geometric design consistency, and the accident rate, while the cost-benefit analysis considers only the accidents with consequences on human health (safety). This difference substantiates why the road S47, the third more dangerous road according to the index *I*, does not appear in Table 15. The data of the road S47 highlight that it has a high hazard index because its high level of AADT, more than its accident rate (medium level). This aspect highlights the importance to consider both economic and risk analyses to avoid overlook severe conditions which only one approach could fail to analyse and correct. Indeed, the risk analysis permits to consider transportation, geometrical and structural issues, or to overcome some limits of the exclusively and safety-related approach. For example, the exposed cost/benefit analysis is based on the hypothesis of rehabilitation on the overall road. This assumption never

**Table 15 – Length and *I* values for the road network.**

| Road | Length (km) | *I* (%) II | Road | Length (km) | *I* (%) III | Road | Length (km) | *I* (%) IV | Road | Length (km) | *I* (%) V |
|---|---|---|---|---|---|---|---|---|---|---|---|
| S29 | 15 | 3.87 | S2 | 30 | 6.95 | S55 | 20 | 10.78 | S58 | 7 | 12.15 |
| S17 | 10 | 3.87 | S32 | 10 | 6.51 | S42 | 10 | 10.14 | S37 | 5 | 12.10 |
| S43 | 26 | 3.65 | S12 | 10 | 6.28 | S26 | 10 | 10.10 | S47 | 10 | 11.81 |
| S21 | 7 | 3.55 | S27 | 5 | 6.08 | S39 | 5 | 9.91 | | | |
| S20 | 15 | 3.50 | S9 | 30 | 5.80 | S7 | 10 | 8.42 | | | |
| S14 | 5 | 3.31 | S13 | 15 | 5.77 | S59 | 10 | 8.29 | | | |
| S51 | 20 | 3.31 | S49 | 30 | 5.77 | S60 | 13 | 8.09 | | | |
| S35 | 10 | 3.26 | S36 | 30 | 5.67 | S46 | 15 | 7.92 | | | |
| S24 | 12 | 3.25 | S8 | 15 | 5.40 | S57 | 10 | 7.70 | | | |
| S16 | 25 | 3.18 | S28 | 20 | 5.02 | | | | | | |
| S11 | 35 | 3.16 | S5 | 20 | 4.80 | | | | | | |
| S56 | 25 | 3.14 | S23 | 23 | 4.61 | | | | | | |
| S48 | 10 | 3.07 | S25 | 28 | 4.51 | | | | | | |
| S10 | 15 | 3.03 | S22 | 10 | 4.42 | | | | | | |
| S44 | 35 | 2.97 | S15 | 10 | 4.20 | | | | | | |
| S19 | 30 | 2.95 | S33 | 10 | 4.20 | | | | | | |
| S30 | 10 | 2.80 | S31 | 40 | 4.17 | | | | | | |
| S6 | 20 | 2.80 | | | | | | | | | |
| S34 | 15 | 2.77 | | | | | | | | | |
| S54 | 15 | 2.68 | | | | | | | | | |
| S40 | 22 | 2.56 | | | | | | | | | |
| S41 | 14 | 2.29 | | | | | | | | | |
| S45 | 10 | 2.22 | | | | | | | | | |
| S1 | 15 | 2.18 | | | | | | | | | |
| S38 | 8 | 1.96 | | | | | | | | | |
| S3 | 25 | 1.68 | | | | | | | | | |
| S52 | 10 | 1.53 | | | | | | | | | |
| S53 | 15 | 1.48 | | | | | | | | | |
| S50 | 15 | 1.36 | | | | | | | | | |
| S18 | 30 | 1.28 | | | | | | | | | |
| S61 | 5 | 0.85 | | | | | | | | | |
| S4 | 10 | 0.72 | | | | | | | | | |

permits the allowance to make priority interventions due to the assumed budget constraint. Critical cases are possible when rehabilitation cost of a road exceeds the available resource; it may appear that roads with lower B/C ratio will be rehabilitated instead of ones with higher B/C ratio. In these cases, the procedure could be modified reducing the rehabilitation works on the priority roads or considering only homogeneous branches of the priority roads in such a way that available resource could be used to rehabilitate them.

**Table 16 – Results of A1, A2, A3 analyses.**

| Analysis | Rehabilitation cost (k€) | Benefit (k€) | Road | Class before works | Position before works |
|---|---|---|---|---|---|
| A1 | 968.9 | 1958.1 | S7 | IV | 8 |
| | | | S60 | IV | 10 |
| A2 | 1909.5 | 3382.0 | S7 | IV | 8 |
| | | | S32 | III | 14 |
| | | | S37 | V | 2 |
| | | | S39 | IV | 7 |
| | | | S58 | V | 1 |
| | | | S60 | IV | 10 |
| A3 | 3866.5 | 4260.4 | S7 | IV | 8 |
| | | | S13 | III | 18 |
| | | | S26 | IV | 6 |
| | | | S27 | III | 16 |
| | | | S32 | III | 14 |
| | | | S37 | V | 2 |
| | | | S39 | IV | 7 |
| | | | S42 | IV | 5 |
| | | | S58 | V | 1 |
| | | | S60 | IV | 10 |

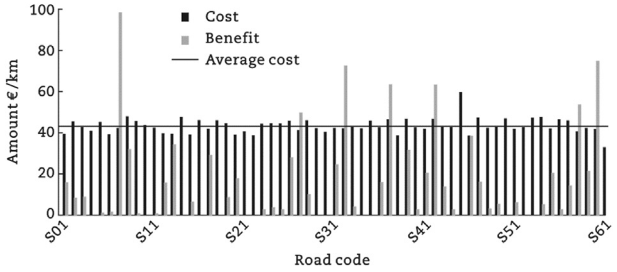

Fig. 6 – Cost and benefit per kilometre.

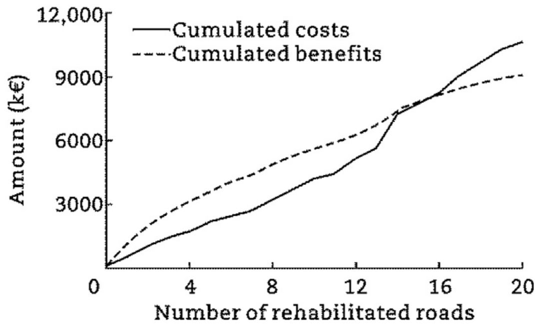

Fig. 7 – Cumulated benefits and costs curves.

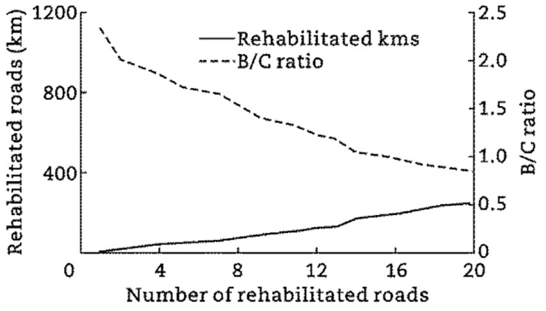

Fig. 8 – B/C ratio and rehabilitated kilometre curves.

## 4. Conclusions

The interest in safety-related road issues has significantly increased in last decades. Often, the safety and risk analysis are conducted using a qualitative rather than a quantitative method, providing weak and far from reliable results. However, the safety evaluation of a road requires a more thorough investigation, without overlooking geometrical and local data of its roadsides.

At this purpose, the proposed methodology allows the prioritization of rehabilitation works to improve roadside safety. The study depends on the assumed ranges of variables and risk classes, as well as on the values attributed to the variables necessary for the hazard index. Therefore, the presented approach aims at proposing a method, based on the visual inspection of the network, that could be modified and adapted to different demands and perception of the problem. However, the data collection represents a useful database for other applications and surveys of the state of safety barriers. It identifies four categories of defects/elements that affect the hazard index related to roadsides (i.e., safety barriers, discrete obstacles, continuous obstacles, water drainage). Regarding a rural road network, the procedure catalogues its stretches considering their hazard index. The obtained results allow the management body to identify and decide the strategic priorities about interventions of roadside rehabilitation.

Survey data, combined with geometric and traffic data of the network, contribute to the assessment of the hazard index, which could be used in decision-making processes. The procedure can be adapted to various framework conditions varying the values of considered coefficients.

At the end of the risk assessment, the cost-benefit analysis permits to identify the rehabilitation conditions that ensure the best strategies for reducing the average density of accidents costs. A B/C ratio more than 1 has been assumed as essential condition to rehabilitate roadsides by mean new barrier installation, removal and new barrier installation, and new terminal installation.

The results obtained from the proposed risk method are consistent with those obtained using the cost-benefit analysis to ensure higher level of roadside safety. The comparison highlights that the risk analysis has a broad vision for the problem, more than the economic analysis because considers not only the accident rate but also the AADT and the geometric design consistency. Moreover, the benefit/cost approach gives results only along road stretches where accidents occurred. Indeed, only in these cases, it is possible to quantify the benefit as reduction of social costs related to deaths, serious injuries and minor injuries, otherwise, it is only possible to assess the costs related to rehabilitation works, which could be necessary, but it is not possible to assess the related benefits. Therefore, the use of both approaches avoids overlooking severe conditions and permits a more correct and proper rehabilitation strategy having not-infinite available budget.

The authors believe that the approach being pursued here is a useful method to prioritize rehabilitation works on safety barriers. Indeed, it overcomes the difficulties of managing partial interventions and geometrical and performance transitions between old and new barriers, as is usually the case when priority interventions involve safety barriers on structures.

## Conflicts of interest

The authors do not have any conflict of interest with other entities or researchers.

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