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Optimal planning of safety improvements on road sites belonging to different categories within large networks: An integrated multi-layer framework

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ABSTRACT

Planning road safety interventions on large road networks implies several layers of complexity in the decision-making process. In fact, the following simultaneous problems should be addressed: estimating safety performances on the different road elements of the network, identifying sites showing high potential for improvement with respect to reference values, defining the possible types of safety measures to be implemented and their anticipated effect on traffic safety, limiting the number of interventions given fixed budget constraints.

This study proposes an integrated multi-layer framework which takes into account the above-defined problems into a single optimization procedure which provides the number and type of safety interventions to be implemented over a wide road network composed of different categories of road elements. The proposed framework is based on the following peculiar aspects: the potential for safety improvement is quantitatively assessed based on the estimation of safety performances for each road category, a bi-level thresholding process integrated in the optimization process is used to highlight sites for interventions, the anticipated outcome of safety measures is quantitatively assessed as well through available crash reduction factors.

The proposed methodology is applied to a case study which analyzes a sample of real roads belonging to a province-wide road network composed of various road elements (i.e., different categories of segments and intersections), under different budget constraints. Results demonstrate the applicability and flexibility of the proposed approach, which could be used for planning purposes, independently of the particular geographic location. Clearly, the approach is valid at the planning stage, given that several details of the different layers of analysis are necessarily simplified, while they should be studied in detail at the single intervention project stage.

1. Introduction

Reducing traffic crashes and, in particular, fatalities and injuries, is among the main objectives of key international planning strategies related to safe and sustainable mobility in both the urban and rural environment (ELTIS Guidelines, 2019; PIARC, 2019; US DOT, 2023). Most of these safety strategies entail intervening by means of specific policies and infrastructural interventions, which can be of different types depending on the peculiar targets to be achieved and on the available budget. Going from the highest to the lowest level (i.e., from international targets, such as those of the European Union; to local targets, such as those specific of counties/provinces and/or single municipalities), these concepts are applied at different scales and with different details.

For what concerns safety-based infrastructural interventions on existing roads, there is a considerable amount of research on the effect of given countermeasures, which are often valid for some specific road categories and/or road elements such as different families of segments and intersections (e.g., Daniels et al., 2019; Elvik, 2017; Cafiso et al., 2017; Thomas et al., 2008). However, when high-level strategies should be implemented, the focus is shifted from a single road site to a global network perspective, considering the network managed by the same highway agency (Saha and Ksaibati, 2016; Persia et al., 2016; Wang et al., 2012; Sørensen and Elvik, 2007). In this optic, the problem involves several concurrent aspects such as: a) the choice of relevant safety indicators to measure safety performances (see e.g., Wang and Feng,

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2019), b) the optimal identification of road sites for interventions (e.g., Alluri and Ogle, 2012), c) the selection of possible appropriate safety measures to solve the identified issues (e.g., Bahar et al., 2016), d) economic assessments based on the available budgets and the intervention costs (see e.g., Mishra et al., 2015; Augeri et al., 2021). While there is a relevant amount of research on each of these four aspects, they are less frequently globally treated in overall integrated frameworks, including in particular economic assessments.

For instance, the search for the most effective countermeasures should cope with the presence of limited budgets available for the road network safety management. This constraint often governs the decision-making process, but it is often ignored, as highlighted in previous literature (Saha and Ksaibati, 2016; Byaruhanga and Evdorides, 2021). Byaruhanga and Evdorides (2021) conducted an extensive literature review on methodological frameworks for safety analyses including economical assessments. They have found a total of 903 studies dealing with these aspects, but just 12 were propaedeutic to outline methodological frameworks for safety interventions with respect to economic boundaries, which, in their opinion, must represent a starting point for safety interventions. In this optic, Martensen et al. (2018) proposed how to define intervention priority based on economic evaluations but considering single infrastructural measures only. This evaluation was based on crash reductions estimated through CMFs (Crash Modification Factors) and costs based on European estimates. Harwood et al. (2010) used CMFs as well, but costs based on American estimates. On the other hand, the UK-based iRAP ([iRAP] International Road Assessment Programme, 2015) attempted to outline risk maps and ratings for road sites, and construction/reconstruction costs related to safety-based countermeasures.

The above cited studies had the advantage of considering the costs of implementation and maintenance of safety measures in cost-benefit (see also D'Agostino, 2016) or cost-effectiveness analyses, but they do not integrate this procedure with other aspects, such as budget constraints or different prioritizations of safety interventions. This gap was partially filled by Saha and Ksaibati (2016), who provided a rational methodology for the traffic safety management system of county roads in Wyoming (United States). This system considered limited funds for interventions, crash reduction factors and costs related to given countermeasures, becoming a multi-objective optimization problem (see also Mishra et al., 2015). The proposed methodology could be transferred to other contexts, after some necessary modifications in data. An important aspect of the proposed traffic safety management system is that different intervention strategies could be planned considering different priorities within the threshold set by the maximum available budget. Thus, the cited study can be considered as a step towards a systematic methodological framework needed for adequately allocating limited budgets for road safety interventions on a network composed of different elements.

A crucial aspect in this sense is to rely on estimates of the safety performances of different categories of road elements. They can be potentially assessed through several procedures, providing different results. Some methods proposed in previous research can tackle this problem by defining the relative risk of road sites belonging to a given family of elements with respect to reference average values for the same family (see e.g., Kononov and Allery, 2003; or the methods listed in: (AASHTO, 2010). However, while relative risks can be defined through appropriate procedures, the definition of thresholds for identifying the so-called "hotspots" (see e.g., Elvik, 2008a; Huang et al., 2009 or Montella, 2010), that is defining when the difference with respect to average values becomes inacceptable, is not straightforward. In the perspective of an integrated traffic safety management framework, this represents another fundamental layer of complexity for successful planning strategies (see e.g., Hussain et al., 2023; Mohammed et al., 2023), independently of the particular procedure used.

All the above-mentioned aspects are the key features which can be used by road agencies to define the priority of safety interventions, by optimally allocating available budgets. As previously remarked, all these steps, singularly taken, are supported by robust literature. However, there is still a gap regarding how to efficiently link all the steps, going from the estimation of safety performances on all sites belonging to a road network to the choice of treatments for sites with highlighted potential for improvement, through straightforward procedures which can be used in the planning practice.

Starting from this, an overall integrated methodological framework for traffic safety management of a road network managed by the same highway agency is proposed in this study. In particular, this framework aims at defining a methodology to identify which road elements should be prioritized for safety interventions, by considering:

- the categorization of road sites in the same network into different families (e.g., different types of segments and intersections), with different reference average crash frequencies;
- the estimation of the relative risk of each road site with respect to the average values and the definition of variable thresholds for interventions, that is integrating the selection of possible hotspots into the methodology (not considering "a-priori" hotspots);
- different possible alternative types of countermeasures (having different costs) for each road site belonging to each category;
- limits in the available budget which constrain the number and types of interventions to be planned;
- different budget values to simulate different priorities of interventions.

Each of these aspects represents a layer of the above-defined complex problem, usually faced while planning safety interventions on large road networks. The integration between these several different layers of analysis necessarily implies that some details of each layer should be relaxed or simplified, to promote the integration between different aspects. This means that the granularity of each layer of analysis should be compatible with the other layers, without preferring the complexity of one aspect above the others, pushing towards optimality.

In the following section, the framework is presented by specifying all the analysis layers. After, the proposed methodological framework is applied to a case study. The obtained results are discussed with reference to the existing literature and to possible practical implications and limitations.

2. Methods

In this section, the problem is firstly formally specified. After, the proposed methodological framework is defined through steps. The case study for the framework application is then illustrated.

2.1. Problem specification

Let us assume that a highway managing agency wants to prioritize safety interventions on its road network. The managed road network is composed of n road sites and, among them, m segments and p intersections. Each segment and each intersection can be assigned to a given reference category c, thus distinguishing between the specific c_s segment category (e.g., two-way two-lane rural road, undivided multilane highway, freeway, etc.) and the specific c_i intersection category (e.g., unsignalized intersections, signalized intersection, roundabouts, junctions, etc.), where q_s and q_i are the total number of, respectively, segment and intersection categories. The total number N of managed road sites (each road site can be defined as $r_{t,c}$, where t is the type of site: segment or intersection, and c is the reference category) is:

$$N = \sum_{k=1}^{c_s} \sum_{i=1}^{m} s_{i,k} + \sum_{l=1}^{c_i} \sum_{j=1}^{p} i_{j,l} \tag{1}$$

Where:

$s_{i,k}$ = generic i-th segment s belonging to the k-th category c_s
$i_{j,l}$ = generic j-th intersection i belonging to the l-th category c_i

In the context of a safety improvement policy, the agency has the following objectives:

- reducing road traffic crashes as much as possible,
- efficiently allocating resources, constrained by a maximum budget B.

Let as assume as well that Safety Performance Functions (SPFs) are available for each managed road category, so that it is possible to predict a crash frequency for each road site $r_{t,c}$, according to a model structure similar to the following (Hauer, 2015; Høye and Hesjevoll, 2020):

$$(f_p)_c = \alpha_c L_r AADT^{\beta_c} \tag{2}$$

where:
$(f_p)_c$ = predicted crash frequency (crashes/year) for a road site $r_{t,c}$ (segment or intersection) belonging to the road category c;
L_r = length of the road site (km), equal to 1 in case of intersections (length is not applicable);
AADT = annual average daily traffic (vehicles/day)[1];
α_c, β_c = coefficients of the model.

If the observed crash frequency f_o (crashes/year) referred to a given period Y (number of years) is known for each road site $r_{t,c}$, then the expected crash frequency can be estimated by means of the Empirical-Bayesian (EB) method (Hauer et al., 2002; Elvik, 2008b; Persaud et al., 2010):

$$(f_e)_{r,c} = (f_p)_c w_c + (f_o)_{r,c}(1 - w_c) = (f_o)_{r,c} + w_c\left((f_p)_c - (f_o)_{r,c}\right) \tag{3}$$

where:

$(f_e)_{r,c}$ = expected (EB-corrected) crash frequency (crashes/year) for a road site $r_{t,c}$ (segment or intersection) belonging to the road category c;
w_c = statistical weight assigned to the predicted crash frequency, which is determined as in the following Eq. (4), depending on the overdispersion parameter k_c (following the hypothesis that SPFs are estimated considering a negative binomial -NB- distribution of the errors) typical of each SPF.

$$w_c = \frac{1}{1 + k_c (f_p)_c Y} \tag{4}$$

Thus, by combining Eqs. (2), (3) and (4), it is possible to estimate an expected crash frequency for each road site r (segment or intersection) belonging to a given road category c.

Crash frequencies per unit of length (crashes/year/km) for all road sites being segments can be obtained by dividing crash frequencies referred to the whole section by the length L_r. The observed, predicted and expected crash frequencies per unit of length are henceforth referred to as, namely, $\left[(f_o)_{r,c}\right]_u$, $\left[(f_p)_{r,c}\right]_u$, $\left[(f_e)_{r,c}\right]_u$. Clearly, in case of intersections, crash frequencies per unit of length coincides with the initially specified frequencies.

The identification of road sites which may be optimal candidates for safety improvements can be based on several different performance measures, also depending on data availability (i.e., crash frequencies, crash rates or more refined measures, see AASHTO, 2010). If SPFs are available, a robust method consists in comparing the expected crash frequencies f_e of road sites (per unit of length) with the average predicted crash frequency f_p for a road site belonging to the same road category derived from an appropriate SPF (per unit of length). In particular, the exceeding crash frequency with respect to the mean for a unit of length, can be calculated:

$$\begin{aligned}\left[(\Delta_e f)_{r,c}\right]_u &= \left[(f_e)_{r,c}\right]_u - \left[(f_p)_c\right]_u = \left[(f_o)_{r,c}\right]_u + \frac{\left[(f_p)_c\right]_u - \left[(f_o)_{r,c}\right]_u}{1 + k_c\left[(f_p)_c\right]_u Y} - \left[(f_p)_c\right]_u \\ &= \left(\left[(f_o)_{r,c}\right]_u - \left[(f_p)_c\right]_u\right)\left(\frac{k_c\left[(f_p)_c\right]_u Y}{1 + k_c\left[(f_p)_c\right]_u Y}\right)\end{aligned} \tag{5}$$

where:

$\left[(\Delta_e f)_{r,c}\right]_u$ = exceeding crash frequency per unit of length calculated for the road site $r_{t,c}$ (segment or intersection) belonging to the road category c.

Defining a threshold for considering a road site as a good candidate for safety interventions, that is, defining a minimum value for $\left[(\Delta_e f)_{r,c}\right]_u$ is the core of the problem. Defining a threshold depends on a trade-off between budget availability and target reduction of crashes. However, if a highway agency manages a road network composed of several different categories, the same budget should be simultaneously used for reducing crashes for all the road categories, while achieving an overall target crash reduction. In this frequent case, the problem transforms into the complex task of simultaneously defining thresholds for each road category.

2.2. *Proposed framework*

In this study, a conceptual multi-layer framework is presented, which is here proposed to solve the problem specified in the previous subsection. The framework is thought for a planning stage (i.e., a mobility plan, a road safety implementation plan, etc.), in which highway agencies should identify optimal candidates (segments or intersections of different categories) for safety interventions among their managed networks. Its steps are graphically schematized in next Figure.

2.2.1. *General concepts*

This framework uses the following concepts:

- it is possible to estimate the outcome of given safety measures starting from previous specific conditions based on Crash Modification Factors (CMFs)/Functions (Hauer et al., 2012; Srinivasan et al., 2012);
- it is possible to implement different road safety measures (or "countermeasures") for the same road site $r_{t,c}$, with various degrees of potential effectiveness measured through CMFs, considering also that different countermeasures (or set of countermeasures, see Elvik, 2014; Colonna et al., 2018; Colonna et al., 2019) have different costs;
- for a given road site category c and a given level of traffic (AADT), it is possible to determine the average predicted crash frequency $\left[(f_p)_c\right]_u$ from a reference SPF function (see Fig. 2 below);
- a road site can be highlighted as a good candidate for safety interventions if its expected crash frequency $\left[(f_e)_c\right]_u$ is higher than a threshold, which can be defined as a curve shifted of a given number

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[1] SPFs for intersections may include both main and secondary AADT at the intersection, thus leading to a variant of the Eq. (2): $f_\rho = kAADT_m^{\beta_1} AADT_s^{\beta_2}$. Otherwise, AADT in Eq. (2) is the total traffic at the intersection.

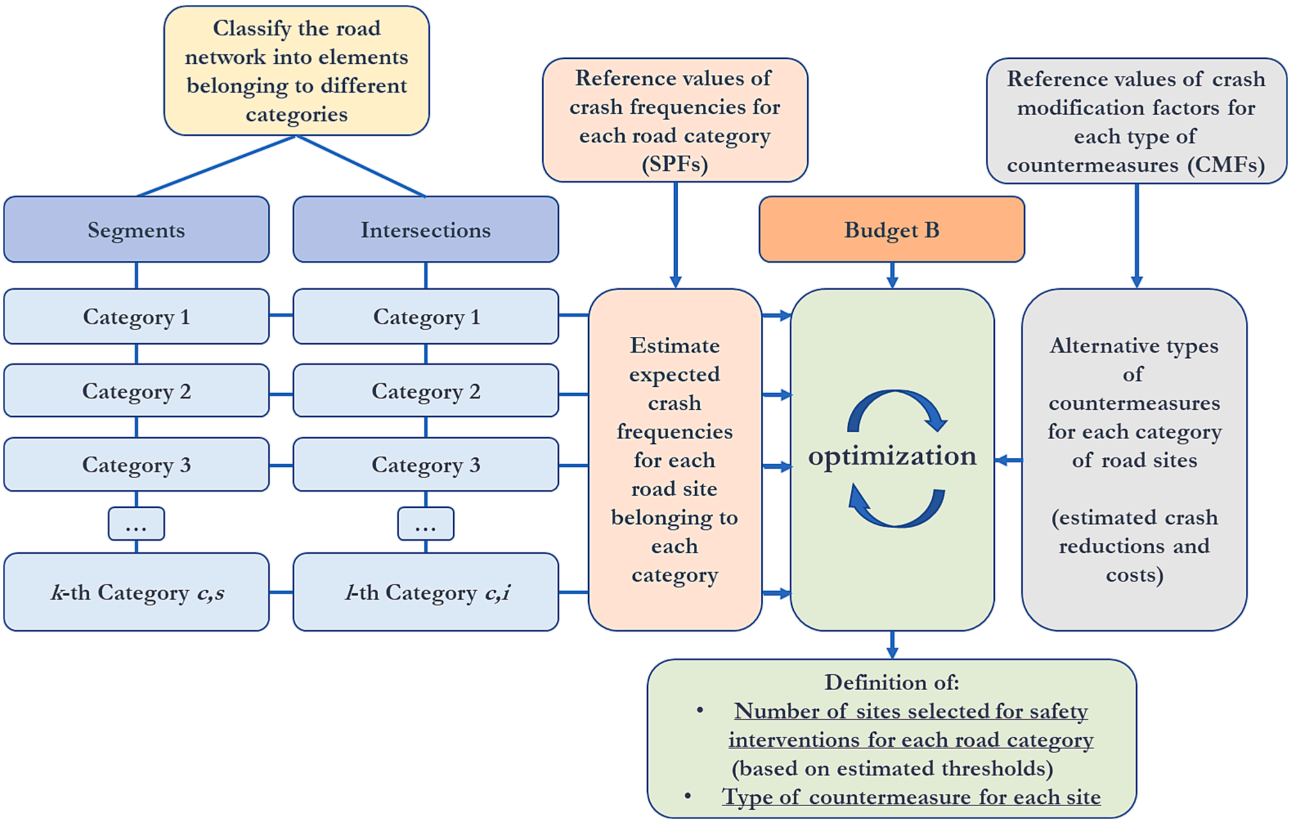

Fig. 1. Graphical scheme of the multi-layer conceptual framework.

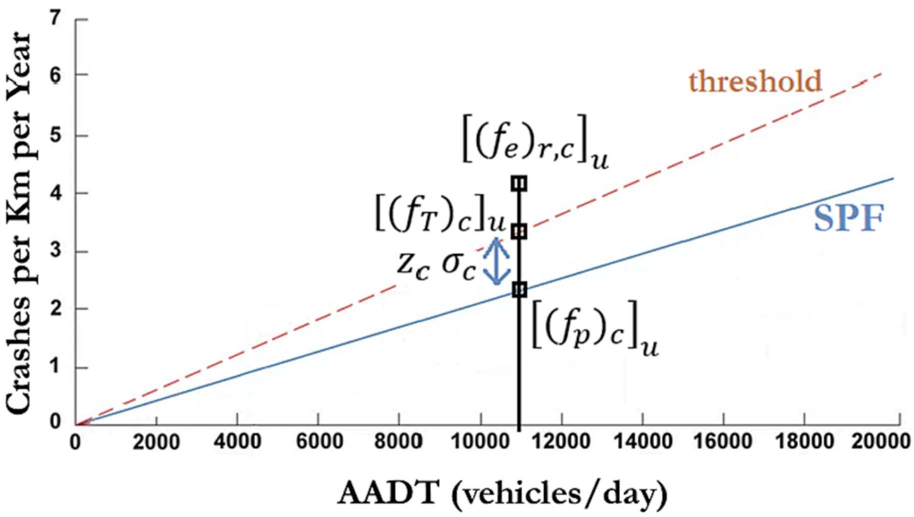

Fig. 2. Graphical representation of point crash estimates corresponding to a generic traffic volume for a given road category.

of standard deviations from the mean value $\left[(f_p)_c\right]_u$ taken from the reference SPF, as in the following Eq. (9) (Kononov et al., 2003[2]):

$$\left[(f_T)_c\right]_u = \left[(f_p)_c\right]_u + z_c\,\sigma_c \tag{6}$$

where:

$\left[(f_T)_c\right]_u$ = threshold set, for each traffic volume, for identifying best candidates for safety interventions among the road sites of a given category c (crashes/year/km), thus for these candidate sites: $\left[(f_e)_{r,c}\right]_u > \left[(f_T)_c\right]_u$

σ_c = standard deviation of the crash frequency distribution around the mean; if the reference SPF is based on an underlying negative binomial distribution of the errors, then $\sigma_c = \sqrt{\left[(f_p)_c\right]_u + k_c\left[(f_p)_c\right]_u^2}$

z_c = standard deviation multiplier: for each category c, it defines how far the threshold is from the reference SPF.

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[2] alternatively, the threshold may correspond to a high percentile of a given probability distribution with mean value $\left[(f_p)_c\right]_u$(Kononov et al., 2015).

2.2.2. *Data requirements*

In order to apply the equations from 2 to 6, the proposed framework necessarily requires the following information:

- crash data (eventually disaggregated into severity classes and/or crash types), traffic volumes and segment lengths for all the road sites in the analysed network;
- a model for predicting crash frequencies (SPF) for each road category in the network (the model should be in the form of Eq. (2) and be provided with the overdispersion parameter k: Negative Binomial model);
- a CMF for each proposed countermeasure, as described in the following sub-sections.

It is evident that those requirements could be not entirely met. In particular, it is usually impossible to have traffic volume data for all the segments in a wide context (province, region, country). However, if the framework is applied within a mobility or safety plan, a network-wide traffic simulation is usually performed. Road sites for which measured traffic volumes are not available can be coupled with simulated traffic volumes (usually peak hour volumes to be converted into daily flows) or, in the worst-case scenario, transferred from similar sites.

On the other hand, crash data and basic geometric information such as segment lengths are easily retrievable and manageable through GIS platforms. Crash data may often be limited to fatal + injury (FI) crashes. However, this does not constitute an issue since the reduction target often refers to FI crashes. In some cases, depending on the implemented planning or policy action, only fatal crashes or crashes of a defined type can be targeted.

SPFs and CMFs may not be immediately available for each road category in the network. While it may be preferrable to use local models, this is often impracticable and then, models developed for other jurisdictions should be transferred to the local context (e.g., those provided by AASHTO, 2010). Clearly, the transferability process poses several problems, and it is not without limitations (see e.g., Srinivasan et al., 2013; Farid et al., 2016; Intini et al., 2019). Moreover, it could be necessary to adapt models developed for road categories which are similar but not identical (e.g., freeways instead of multi-lane access-controlled divided highways), if specific SPFs are not available. The same issues are valid for CMFs as well (Hauer et al., 2012) as the related solutions (see e.g., AASHTO, 2010 or the online sources: CMF Clearinghouse,[3] PRACT Repository[4]).

2.2.3. *Definition of possible countermeasures*

The determination of optimal countermeasures is a complex task, which includes several layers of analysis (Elvik, 2014). It should be based on an accurate diagnostic stage, in which specific safety measures are tailored to the site conditions and to the evident or implicit infrastructural deficiencies, considering also the history of crashes (see e.g., Colonna et al., 2018). However, in the perspective of a network-wide intervention planning stage, the granularity of this study (definition of countermeasures) cannot be microscopic (i.e., referred to the specific conditions of a given site). Nevertheless, a minimum level of diagnosis is required to ensure that countermeasures are really applicable to the considered road sites. Hence, trying to incorporate a preliminary definition of countermeasures into the planning stage poses potential logical inconsistencies.

The definition of possible countermeasures at the planning stage can be solved in three ways, which should be regarded as incremental steps:

1) hypothesizing different types of "standard" countermeasures (e.g., three types of countermeasures, with different costs) for sites belonging to each road category (e.g., two-way two-lane rural segments, signalized intersections, etc.), without conducting any preliminary diagnostic analysis of safety problems of each specific road site;
2) hypothesizing different types of countermeasures for each road site, based on a preliminary diagnostic analysis of safety problems;
3) hypothesizing tailored countermeasures for each road site after a detailed diagnostic analysis of safety problems.

The proposed framework is compatible with all the three above-defined approaches. However, clearly, choosing between the three alternatives depend on the network extension, the available time and the availability of additional specific information about road sites. While using the first approach (e.g., in case of wide networks, for preliminary decisions), opting for "standard" countermeasures is always conditional to the specific road category. For example, for unsignalized intersections, it is possible to: 1) improve road signs and introduce traffic medians, 2) implement traffic signals, 3) convert into roundabout. Of course, not all these countermeasures can be applied to signalized intersections as well. To foster the application of the approaches 2 and 3 (which are clearly more reliable), it is possible to conduct a preliminary network screening to limit the number of road sites which may benefit more from safety interventions. For example, only road sites for which $\left[(\Delta_e f)_{r,c}\right]_u > 0$ may be considered.

Whatever the employed approach is, it is paramount that the definition of countermeasures is only preliminary and useful to identify the potential best candidates for safety interventions at the planning level. At the more detailed project level, countermeasures should be tailored for each specific road site.

2.2.4. *Definition of crash reductions and costs*

Once countermeasures are defined, CMFs can be associated to each countermeasure. Thus, it would be possible to calculate the potential crash reduction as follows:

$$(\Delta_{b-a}f)_{r,c} = (f_e)_{r,c} - CMF_{x,c}(f_e)_{r,c} = (f_e)_{r,c}(1 - CMF_{x,c}) \tag{7}$$

where:

$(\Delta_{b-a}f)_{r,c}$ = expected yearly crash reduction after the hypothesized safety intervention on the road site $r_{t,c}$ (crashes/year) calculated as the difference between the estimate in the before "b" and after "a" periods;
$CMF_{x,c}$ = x-th CMF applicable to the category c (the number of X CMFs for each category depends on the number of hypothesized countermeasures for each category);

Thus, the total crash frequency reduction on the road network CR (%) and related total expenses TE (€) are:

$$CR = \frac{\sum_{k=1}^{c_s}\sum_{i=1}^{m}(\Delta_{b-a}f)_{i,k} + \sum_{l=1}^{c_i}\sum_{j=1}^{p}(\Delta_{b-a}f)_{j,l}}{\sum_{k=1}^{c_s}\sum_{i=1}^{m}(f_e)_{i,k} + \sum_{l=1}^{c_i}\sum_{j=1}^{p}(f_e)_{j,l}}100(\%) \tag{8}$$

$$TE = \sum_{k=1}^{c_s}\sum_{i=1}^{m}E_{i,k} + \sum_{l=1}^{c_i}\sum_{j=1}^{p}E_{j,l} \tag{9}$$

Where $E_{i,k}$ and $E_{j,l}$ are the implementation costs referred to the safety measures considered for, namely, each segment and intersection in the network.

Note that CR is a percentage referred to a generic year (crash frequencies are involved in the calculation) following the implementation of safety measures, assuming that the effect of countermeasures will not change over the future years. On the other hand, total expenses may include both immediate investment costs and annual maintenance costs, considering discounted values depending on the service life.

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[3] CMF Clearinghouse: https://www.cmfclearinghouse.org/.

[4] PRACT EU Project Repository: https://www.pract-repository.eu/.

2.2.5. Optimization problem

Based on the previously reported hypotheses, the optimization problem can be defined.

The optimization problem consists in finding the maximum of Eq. (8) (objective function), that is maximizing the percentage crash reduction. However, such as in real contexts, this objective is constrained by a maximum budget B: $TE \leq B$.

The values of the following variables, corresponding to the maximum of the objective function, are searched:

- z_c multipliers of the standard deviation from the reference average crash frequency (Eq. (6));
- $CMF_{x,c}$ to be applied to each road site belonging to the category c, among a set of possible defined CMFs corresponding to specific safety measures (i.e., three possible safety measures, each with its associated respective CMF, for each site category).

Thus, the optimization problem helps to select road sites for safety interventions and suggests the safety measure to be implemented for each road site among a set of possible measures. Identifying the z_c multiplier of the standard deviation from the mean for each road category implies rationally setting a threshold for interventions above the mean expected crash frequency (Eq. (6)). To ensure intervening on road sites which may realistically benefit from road safety interventions, the following additional constraints are set:

- $z_c > 0$, meaning that only sites showing expected crash frequencies higher than the mean can be selected;
- $\left[(f_e)_{r,c}\right]_u > [\varphi_c]_u$, meaning that sites having expected crash frequencies lower than a value φ_c (a threshold crash frequency value referred to each road category, which does not vary with AADT) cannot be selected.

The latter condition represents a further threshold which is set to avoid selecting road sites for which the first threshold condition is met: $\left[(f_e)_{r,c}\right]_u > [(f_T)_c]_u$, but having very low expected crash frequencies (i.e., lower than φ_c). In fact, in this case, the crash frequency reduction obtainable through countermeasures could be irrelevant.

Hence, we let vary the additional φ_c threshold value together with the other variables (z_c and $CMF_{x,c}$), while searching the optimal combination leading to maximize the objective function (Eq. (8)). In summary, road sites showing expected crash frequencies located in the area highlighted in next Figure, are targeted as candidates for the selected road safety interventions.

2.3. Case study

The proposed framework is here applied to a case study. The case study is based on a province-wide rural road network composed of road sites (segments and intersections) for which crash data were available (observation period: 2015–2019, see also Intini et al., 2022) in the context of the Sustainable Mobility Plan drafted by the Metropolitan City of Bari (Italy).

The optimization is applied to a sample of 145 road sites (20% of all the road sites on which at least one crash was recorded) taken from this network. The sample of road sites was formed in order to represent the actual classification of all road sites in the network into the following road categories:

- two-way two-lane road segments (64 sections, 44% of total sites);
- divided multi-lane segments (6 sections, 4% of total sites);
- three-legged at-grade unsignalized intersections (24 intersections, 17%);
- three-legged roundabouts (3 roundabouts, 2%);
- four-legged at-grade unsignalized intersections (8 intersections, 6%);
- four-legged roundabouts (7 roundabouts, 5%);
- signalized at-grade intersections (4 intersections, 3%);
- grade-separated intersections/junctions (29 junctions, 20%).

For each road category, road sites were randomly selected among the entire population by respecting the only constraint that the annual crash frequency per km should match the population-related frequency per km. This condition, together with the choice of including a number of road sites for each road category reflecting the actual distribution of road categories in the network, was set to rely on a realistic sample of road sites, to simulate a real decision-making process. Note, in fact, that all the main road categories were considered (apart from freeways, which have a very limited length in the province used as a case study and they are managed by a different agency). The main data about the sample of road sites are reported in next Table.

In the case study, the following alternative safety measures are considered, mainly taken from the study by Daniels et al. (2019), unless where otherwise stated. Effectiveness in terms of crash reduction (measured through Crash Modification Factors -CMFs-) and total costs for each countermeasure, taken from the same study, are summarized in the following Table 2.

The optimization problem (see Eqs. (8) and (9)) can be solved

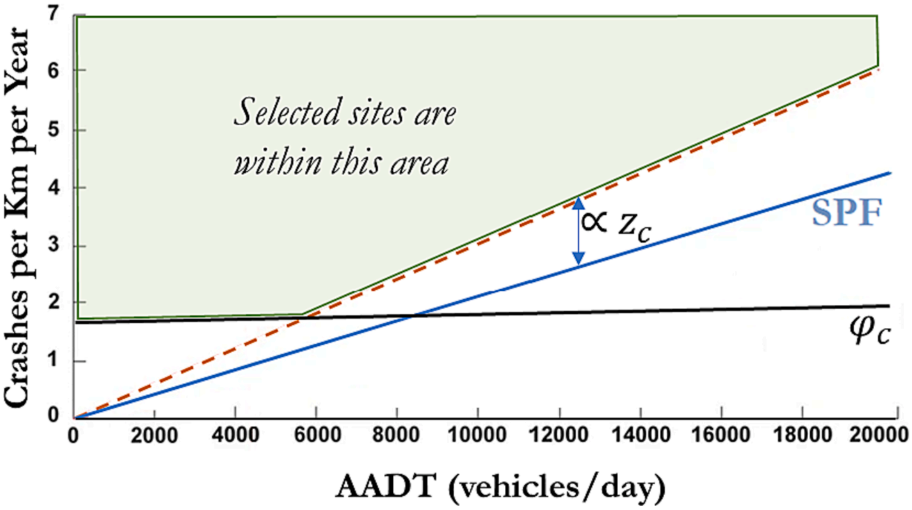


Fig. 3. Graphical representation of the area in which the candidates for safety interventions should lie.

Table 1
Mean values of the collected variables related to the sample of road sites used for the case study application (standard deviations in parenthesis).

Road site category	n	Observed crash frequency (fatal + injury crashes/year/km)	Segment length (km)	Annual Average Daily Traffic (vehicles/day)	Predicted crash frequency (fatal + injury crashes/year/km) (Eq. (3))*	w (weight of EB method) (Eq. (5))*	Expected crash frequency (fatal + injury crashes/year/km) (Eq. (7))
Two-way two-lane segments	64	0.38 (0.33)	4.34 (3.16)	3905 (3820)	0.14 (0.14)	0.82 (0.14)	0.18 (0.17)
Divided multi-lane segments	6	0.60 (0.32)	1.79 (0.84)	22,181 (14008)	0.61 (0.34)	0.56 (0.13)	0.59 (0.29)
Three-legged at-grade unsignalized intersections	24	0.41 (0.57)	–	6333** (4717)	0.37 (0.36)	0.60 (0.22)	0.31 (0.22)
Three-legged roundabouts	3	0.40 (0.20)	–	10290** (1836)	0.07 (0.02)	0.86 (0.04)	0.12 (0.05)
Four-legged at-grade unsignalized intersections	8	0.58 (0.53)	–	5297** (4470)	0.35 (0.30)	0.74 (0.14)	0.35 (0.18)
Four-legged roundabouts	7	0.43 (0.08)	–	7237** (3411)	0.13 (0.07)	0.78 (0.10)	0.19 (0.18)
Signalized at-grade intersections	4	0.75 (0.41)	–	12419** (7321)	0.87 (0.45)	0.69 (0.13)	0.83 (0.42)
Grade-separated intersections/ junctions	29	0.48 (0.29)	–	40225** (27580)	0.49 (0.15)	0.77 (0.05)	0.49 (0.14)

*Values of α_c, β_c, k_c are taken from the Highway Safety Manual (AASHTO, 2010) and calibrated according to a local study (see Colonna et al., 2018, Intini et al., 2019), if possible. Only in case of grade-separated intersections, an ad-hoc SPF was developed and used.
**This is the mean total AADT (sum of the AADT on both the major and minor roads at the intersection).

Table 2
Details about the alternative safety measures considered for the different categories of road sites.

Road site category	Safety Measure 1			Safety measure 2			Safety measure 3		
	Type	CMF*	Cost (M€)	Type	CMF*	Cost (M€)	Type	CMF*	Cost (M€)
Two-way two-lane rural segments	Set of low-cost local treatments for high-risk sites	0.72	0.06	Implementation/ upgrade of safety barriers	0.46	0.07	Automated speed control	0.44	0.15
Divided multi-lane segments	Set of low-cost local treatments for high-risk sites	0.72	0.12**	Implementation/ upgrade of safety barriers	0.46	0.14**	Automated speed control	0.44	0.30**
Unsignalized at-grade (three- or four-legged) unsignalized intersections	Set of low-cost local treatments for high-risk sites	0.72	0.06	Implementation of traffic signals	0.71	0.10	Conversion into roundabout	0.51	0.46
Roundabouts (three- or four-legged)	Set of low-cost local treatments for high-risk sites	0.72	0.06	Channelisation and lighting***	0.66	0.28	Conversion into junction****	0.43	1.24
Signalized at-grade (three- or four-legged) intersections	Set of low-cost local treatments for high-risk sites	0.72	0.06	Channelisation and lighting***	0.66	0.28	Conversion into roundabout	0.51	0.46
Grade-separated intersections/ junctions	Set of low-cost local treatments for high-risk sites	0.72	0.06	Automated speed control	0.44	0.15	Junction enhancement*****	0.30	4.00

*CMFs are intended for fatal + injury (FI) crashes. They are adapted from the study by Daniels et al. (2019), in which CMFs are differentiated into disaggregated severity classes (i.e., fatal, severe injury, slight injury, no injury). CMFs for FI crashes are obtained by weighting CMFs according to the percentage of crashes in the different severity classes (according to AASHTO, 2010).
**Note that total costs for safety measures on four-lane segments are assumed to be double than the costs for two-lane segments (no specific details are provided in the reference study for different road categories).
***This measure combines the two measures -channelisation- and -road lighting- considered by Daniels et al. (2019) and their related costs. Note that in this case channelisation is intended as the enhancement/reshaping of traffic islands and lanes within the intersections.
****Source of CMF is Elvik et al. (2009), costs are based on local estimates.
*****This CMF combines different interventions to enhance the junction (increase the length of acceleration/deceleration lanes, improve horizontal and vertical signs, improve friction). Source of CMFs is the CMF Clearinghouse (2023), costs are based on local estimates.

through different approaches. Given the non-linear nature of the problem, an evolutionary algorithm was used here. However, in this study, a general framework for selecting sites with promises for safety interventions is proposed. Hence, there is no particular emphasis on the methodology used to solve the optimization problem, which can be conducted in different ways (see e.g., Byaruhanga and Evdorides, 2022). Note that the evolutionary algorithm does not entail any optimality testing or particularly restrictive assumptions, thus the provided solution may not coincide with the global optimum and different initial conditions may lead to different results. In fact, the simulation stops when there is no other candidate solution which may significantly improve the obtained result.. Nevertheless, this aspect is compatible with the nature of the problem, in which different candidate optimal solutions may be considered while programming road safety interventions, given that there may be also other external factors influencing the choice between candidates with similar potential for improvement.

In this case study, four different maximum budget values B were set, to represent different possible conditions:

- scenario a) 5 million euros (5 M€);
- scenario b) 10 million euros (10 M€);
- scenario c) 20 million euros (20 M€);
- scenario d) 50 million euros (50 M€).

If all the 145 road sites considered in this case study would have been treated by always implementing the most effective countermeasures (i.e., those with the highest CMFs for each road category), the total cost would have been 191 M€. These treatments would have been associated to a global severe crash percentage reduction equal to 57%. Hence, the four above-defined scenarios (from 5 M€ to 50 M€) represent frequent conditions in which the budget is not sufficient to enhance safety conditions of all segments and intersections in the road network, and priorities should be set. In all the four above-reported scenarios, the application of the proposed framework is aimed at finding the combination of safety measures leading to the maximum crash reduction percentage, given a limited budget constraint.

3. Results

Results obtained from the application of the proposed framework to the sample of road sites presented in the previous section are reported as

Table 3
Results of the optimization procedure for the three budget scenarios.

Variable	Budget B (M€)	Segments		Intersections						Total road network (N = 145)
		2-way 2-lane (N = 64)	Divided multi-lane (N = 6)	3-legged at-grade unsign. (N = 24)	3-legged roundab. (N = 3)	4-legged at-grade unsign. (N = 8)	4-legged roundab. (N = 7)	Signalized at-grade (N = 4)	Grade-separated (N = 29)	
Number of treated sites (T.S.)	5	19 (30%)	0	0	0	0	0	0	0	19 (13%)
	10	27 (42%)	3 (50%)	11 (46%)	0	2 (25%)	4 (57%)	0	10 (34%)	57 (39%)
	20	43 (67%)	3 (50%)	14 (58%)	0	3 (38%)	0	0	16 (55%)	79 (54%)
	50	55 (86%)	3 (50%)	14 (58%)	3 (100%)	4 (50%)	7 (100%)	0	16 (55%)	102 (70%)
T.S. with Safety Measure 1 (SM#1)	5	4 (6%)	0	0	0	0	0	0	0	4 (3%)
	10	7 (11%)	0	11 (46%)	0	2 (25%)	4 (57%)	0	9 (31%)	33 (23%)
	20	4 (6%)	0	14 (58%)	0	3 (38%)	0	0	8 (28%)	29 (20%)
	50	5 (8%)	0	9 (38%)	3 (100%)	1 (13%)	6 (86%)	0	0	24 (17%)
T.S. with Safety Measure 2 (SM#2)	5	15 (23%)	0	0	0	0	0	0	0	15 (10%)
	10	20 (31%)	3 (50%)	0	0	0	0	0	1 (3%)	24 (17%)
	20	39 (61%)	3 (50%)	0	0	0	0	0	8 (28%)	50 (34%)
	50	46 (72%)	3 (50%)	3 (13%)	0	1 (13%)	1 (14%)	0	11 (38%)	65 (45%)
T.S. with Safety Measure 3 (SM#3)	5	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
	20	0	0	0	0	0	0	0	0	0
	50	4 (6%)	0	2 (8%)	0	2 (25%)	0	0	5 (17%)	13 (9%)
Crash reduction (%)	5	−27.8	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−15.0
	10	−36.6	−24.4	−9.4	−0.0	−0.7	−20.8	−0.0	−13.0	−25.5
	20	−47.1	−24.4	−11.0	−0.0	−8.7	−0.0	−0.0	−24.3	−33.2
	50	−49.4	−24.4	−13.6	−28.0	−21.1	−29.1	−0.0	−35.4	−37.8
Total cost (M€)	5	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0
	10	7.3	0.7	0.6	0.0	0.1	0.2	0.0	1.1	10.0
	20	13.3	0.7	0.8	0.0	0.2	0.0	0.0	5.0	20.0
	50	19.4	0.7	1.7	0.2	1.1	0.6	0.0	26.3	50.0
z_c	5	0.14	1.23	0.88	0.82	1.85	2.68	2.28	3.32	–
	10	0.02	0.00	0.04	0.95	0.05	0.08	0.09	0.03	–
	20	0.00	0.03	0.02	3.69	0.08	0.73	0.10	0.00	–
	50	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	–
φ_c	5	0.12	1.57	2.57	1.61	4.04	3.32	3.41	1.64	–
	10	0.11	0.07	0.08	0.98	0.28	0.19	0.39	0.11	–
	20	0.03	0.22	0.02	0.75	0.15	0.27	0.10	0.03	–
	50	0.00	0.00	0.00	0.00	0.02	0.01	0.44	0.09	–

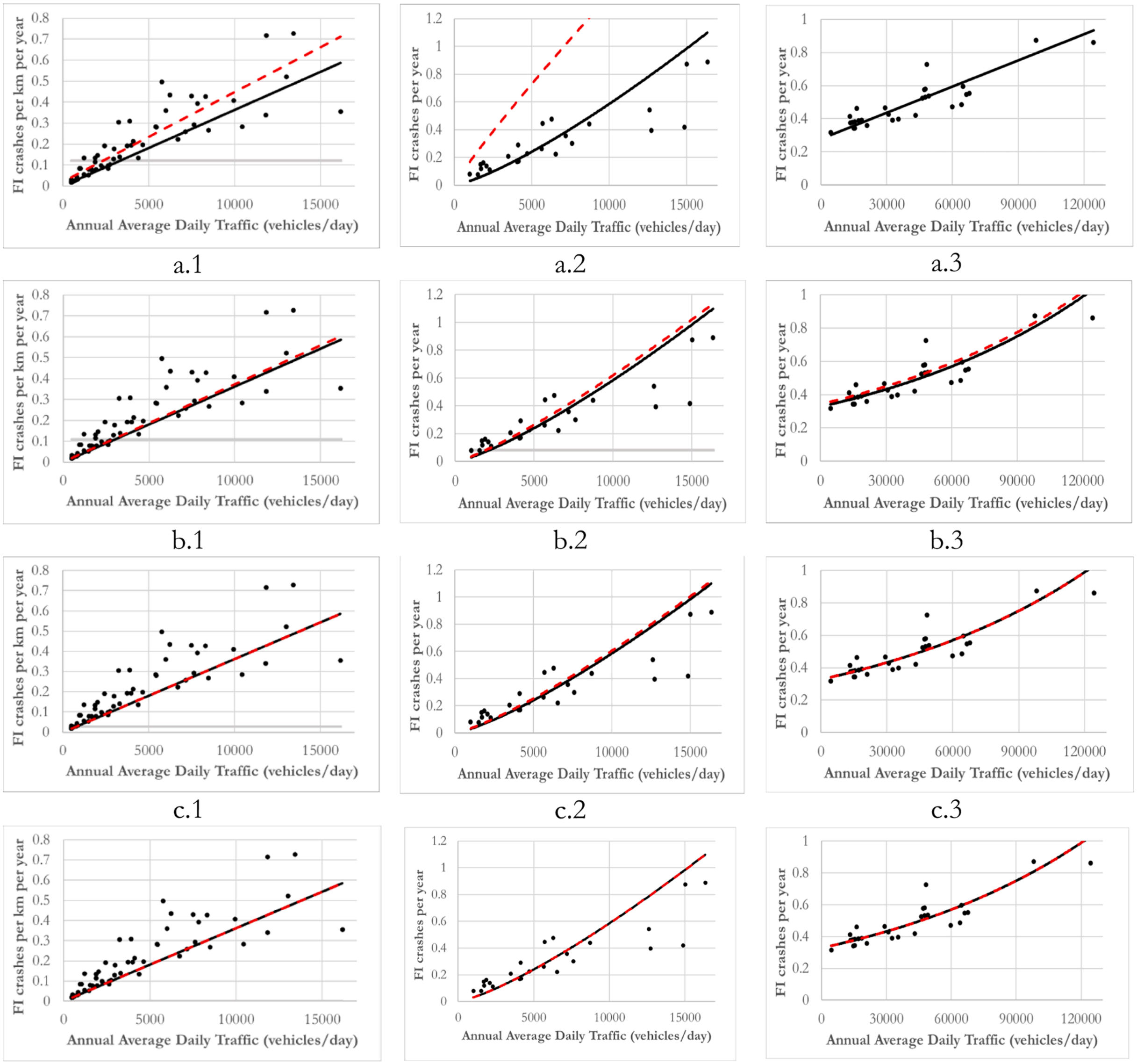
follows.

As it emerges from Table 3, the total number of treated sites ranges from 19 (13% of total sites) in the lowest budget scenario (5 M€) to 102 (70% of total sites) in the highest budget scenario (50 M€). In the intermediate 20 M€ scenario, about half of road sites (79) are prioritized for treatments.

The graphical representations of the thresholds (z_c and φ_c) defined in the previous table are reported in next figure for the three most numerous road categories (two-lane rural roads, three-legged at-grade unsignalized intersections and grade-separated intersections/junctions).

Considering the different road categories, it is evident that, especially for low budget scenarios, the treated sites mostly belong to the most numerous road categories (i.e., two-way two-lane roads, three legged at-grade intersections or grade-separated junctions), as clearly expected. In particular, two-way two-lane road segments are the only sites selected for improvement in the lowest budget scenario. On the other hand, while increasing the budget in the intermediate scenarios, sites from other categories are included within the road sites prioritized by the optimization procedure: multi-lane segments, three- and four-legged unsignalized intersections, four-legged roundabouts and junctions. In the highest budget scenario, the number of treated sites of these categories increase, including also three-legged roundabouts.

Those results depend on the selection of the thresholds based on z_c and φ_c, which vary with the road category and the budget scenario. In this sense, the case of two-way two-lane road segments is particularly explicative. In fact, in the lowest budget scenario (diagram a.1 in Fig. 4) the selection area is delimited by both the dashed red line ($z_c > 0$) and the horizontal grey line ($y = \varphi_c$). In the diagram b.1 (10 M€ scenario), the number of selected sites increase since the selection area increases as well (z_c approaches 0 and φ_c is drastically reduced). In the diagram c.1 (20 M€ scenario), the selection area still increases because z_c equals 0 and φ_c approaches 0 as well, until the highest budget scenario



a.1 a.2 a.3

b.1 b.2 b.3

c.1 c.2 c.3

d.1 d.2 d.3

Fig. 4. Graphical representation of the thresholds defined for each budget scenario: a) 5 M€, b) 10 M€, c) 20 M€, d) 50 M€ and for each of the three most numerous road categories: 1) two-way two-lane road segments, 2) three-legged at-grade unsignalized intersections, 3) grade-separated intersections/junctions. Black lines are the reference SPFs, red dashed lines are the threshold curves defined based on the z_c multiplier, horizontal grey lines are the f_c thresholds independent on traffic volumes (they are represented only when they are determinant for restricting the selection area, that is when they are neither too low nor too high). Note that SPFs for intersections generally depend on both the major and minor traffic volumes, while a simplified bi-dimensional representation is here reported, referred to total volumes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(diagram d.1) in which the area for site selection coincides with the space above the SPF (both z_c and φ_c are equal to 0).

For what concerns the types of safety measures, the low-cost (SM#1) and intermediate (SM#2) measures are the most frequently selected. The most expensive (and effective) safety measure (SM#3) starts being considered only in the highest budget scenario (50 M€).

Results from the optimization procedure should be interpreted along with the theoretical cost needed to implement all the safety measures together: 191 M€, associated to a 57% severe crash reduction. Hence, it is evident that it is possible to achieve almost one half of this crash reduction target (-37.8%) by using only a relatively small available budget (50 M€). If a similar optimization procedure would have not been used, then the anticipated percentage crash reduction could have been significantly lower. Even in case of the smallest budget scenario (5 M€), a not negligible crash percentage reduction (15%) would have been achieved. This will be further discussed in the next section.

4. Discussion

In this section, results obtained from the application of the proposed framework are discussed. Some of the main outcomes from the case study are firstly recalled and, after, findings from this study are put into a broader perspective, in light of previous research.

4.1. Outcomes of the case study

Some of the most relevant outcomes obtained from the case study are discussed in the following. Different road categories were considered in the case study, reflecting the composition of the sample road network used as reference. The percentage of treated road sites for each road category is summarized in the next diagram, for each budget scenario (See Fig. 5).

As already stated, in the lowest budget scenario, the only road sites considered for improvement are two-way two-lane segments. While increasing the budget, other categories are progressively included. However, it can be noted that the growth of treated road sites with the increasing budget is not uniform for all the road categories. The number of two-way two-lane segments progressively increase up to almost all the sample of sites in the highest budget scenario. On the other hand, for some other road categories the percentage of treated road sites settles on a value around 50%, which does not further increase. This is valid also for the two most represented road categories after two-way two-lane roads: three-legged unsignalized intersections and junctions. In some limited cases (roundabouts), the 100% of the few considered road sites is reached in the highest budget scenario. Hence, the difference between this approach for site selection and other possible practical approaches is evident. In fact, another typical approach is selecting road sites which independently exceed some predefined thresholds for each road category (see e.g., Ranieri et al., 2023). In that case, depending on different budget scenarios, one should expect a progressive increase of the treated road sites for each road category (e.g., by progressively lowering the crash frequency threshold). In the proposed approach, which considers the road network as a whole, in the perspective of the highway manager, the proportion of sites selected for interventions may vary from one scenario to the other, according to the overall considered optimization procedure. An example of this statement is the number of treated four-legged roundabouts, which increases from the 10 M€ to the 50 M€ scenario but, goes again down to zero in the 20 M€ scenario. This depends on the optimization procedure, which is applied independently on the particular budget scenario.

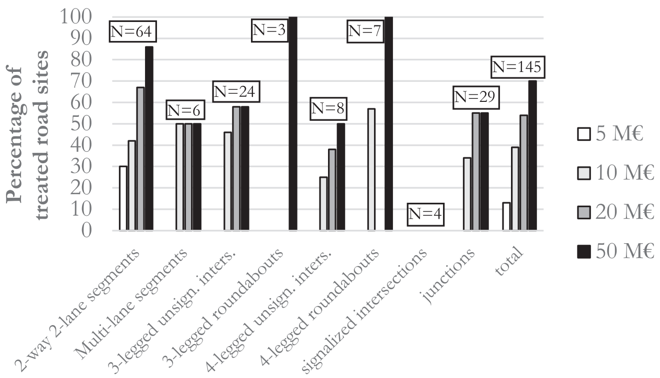


Fig. 5. Percentage of treated road sites for each budget scenario classified according to the road category.

Another layer of the optimization procedure is the selection of a given safety measure for each treated road site among the set of considered measures. Even if different safety measures are considered for each road category, some insights can be gathered by grouping measures by family (see Table 3): SM#1 (low-cost/less effective measure), SM#2 (intermediate measure), SM#3 (expensive/more effective measure). The percentage of road sites treated with safety measures belonging to each family is reported in next Figure for each budget scenario.

The intermediate safety measure (SM#2) is the most frequently selected except than in the 10 M€ scenario, where there is a rapid increase in the selection of the cheapest (but less effective) SM#1, with respect to the lowest budget scenario. However, while increasing the budget, the percentage of sites treated with SM#2 still grows, while the share of selected SM#1 decreases. In the highest budget case, the most expensive (and effective) SM#3 is selected for some road sites. Hence, it is evident that for low budget scenarios, a mix of relatively low-cost safety measures can be selected, depending on the other conditions. This is an expected outcome since, with low budgets, a wide list of small/medium interventions may be more effective than very few massive interventions on a limited number of road sites. These solutions may represent a trade-off between high crash reduction and limited costs. When the available budget increases, there may be room for more expensive interventions on some selected road sites.

The relationship between total costs for safety interventions and the estimated percentage FI crash reduction on the network is represented in next figure.

Fig. 7 evidently shows that the application of the proposed optimization procedure generates a crash reduction-cost boundary curve. Given the selected safety measures, and for each available budget (total cost), it would not be possible to achieve a higher crash reduction than the corresponding value lying on the curve in the previous figure (i.e., for a given available budget, any combination of safety measures and treated sites different than the calculated optimum would lead to a point

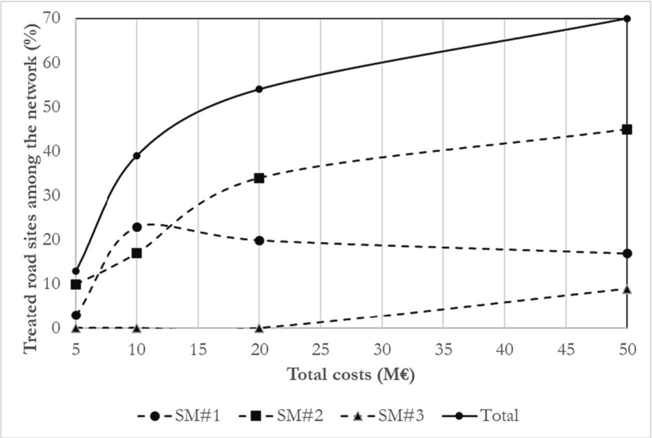


Fig. 6. Distribution of the safety measures selected for the treated road sites in the three considered families.

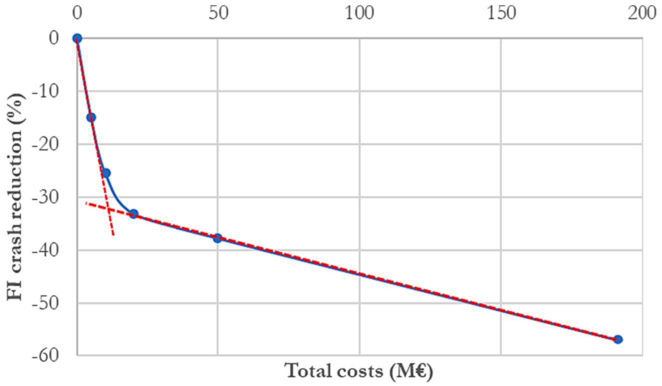


Fig. 7. Relationship between total costs for safety interventions and the associated anticipated percentage FI crash reduction on the network and its bi-linear approximation (red dashed line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

which is above the represented curve). However, this curve follows an approximate bi-linear tendency. In this case, the two lines diverge from the baseline curve in correspondence of a small range (approximately between 10 and 20 M€). The first line (x-axis ranging from 0 to 10 M€) has a very steep slope compared to the second line (x-axis ranging from 20 to 191 M€). In particular, considering data in Table 3, the calculated slope of the first line is an average −2.6% FI crash reduction (with respect to the initial crash frequency) per M€ spent. The slope of the second line is an average −0.1% FI crash reduction (with respect to the initial crash frequency) per M€ spent, which represents a different order of magnitude. This means that after a given budget value (in this case included between 10 and 20 M€), the costs to obtain additional percentage crash reductions (with respect to the initial crash frequency) drastically increase. In this sense, the point where the slope changes may represent a “critical” budget. This result is in line with similar findings presented by Saha and Ksaibati (2016), who identify an "appropriate" intervention budget, after their optimization procedure is applied for different budget scenarios in the case of county paved roads in Wyoming (US).

4.2. Applicability of the proposed framework

The results discussed in the previous section demonstrate the applicability of the proposed framework to a real-world road network (in the presented case, a province-managed road network). It was shown that this framework can be used to prioritize safety interventions on road sites belonging to different categories, by letting vary: a) thresholds for selecting road sites for safety interventions, b) types of countermeasures, constrained by the available budget.

Treating the threshold for selecting road sites as a variable was a key strategy of the proposed framework. In fact, a variable bi-level thresholding process was implemented, based on: a) a threshold which represents a high percentile of the distribution of crash frequencies around the reference mean and b) a crash frequency threshold which does not vary with the traffic volume. Both values significantly vary across the considered scenarios (as shown in the example Fig. 4). This represents an innovation with respect to previous research (Ferreira and Couto, 2013; Washington et al., 2014, Saha and Ksaibati, 2016) in which hotspots are identified with respect to predefined “a-priori” thresholds. Hence, the shift from a traditional prioritization of sites based on fixed thresholds (e.g., above a given high percentile of a predefined distribution, see Kononov et al., 2015) to defining thresholds within the optimization procedure itself can be highlighted as a scientific contribution of this method. This implies the advantage that, in this way, decision-makers are not forced to base their decisions on arbitrary values which may not be entirely rationally determined.

Moreover, another key concept of the traffic safety engineering practice is that different alternative safety measures can be used in the attempt of solving an identified safety issue. Several studies have tried to collect and compare different possible safety measures (see e.g., Elvik et al., 2009; AASHTO, 2010; Fleisher et al., 2016; Daniels et al., 2019). In this study, also the choice of safety measures was kept within the optimization procedure, trying to pursue a trade-off between the highest crash reduction and the lowest expense. In fact, three families of measures were considered for each road category, starting from low-cost/less effective to expensive/more effective measures. It is important to say that the proposed framework could be adapted to different or more numerous safety measures with respect to those considered in the case study. In fact, there could be a particular focus on the types of safety measures to use (e.g., with respect to their cost-effectiveness or their lifespan and scope, such as discussed in Byaruhanga and Evdorides, 2022). However, it is important to say that, independently on the considered safety measures, the proposed framework intervenes at the planning stage and so, the effect of safety measures is anticipated and based on crash reduction factors.

For what concerns budget constraints, the obtained results for different budget scenarios have not a unique practical explanation. In fact, they may reflect: a) different scenarios corresponding to the budget availability of the highway managing agency, b) different progressive intervention priorities. In fact, sites highlighted in the lowest budget scenario (5 M€) may represent those with the highest potential for safety improvement and, simultaneously, sites on which the most urgent interventions should be prioritized. If the available budget is progressively increased, other interventions are added to the previously highlighted sites, following the criterion that the higher the budget, the lower the priority of the additional highlighted sites. This methodology is coherent with the European approach to road network safety management (European Parliament and Council, 2019, see also Persia et al., 2016) and with the practical aspects of funding being scattered over several years rather than being available all at once. For example, planning of safety interventions over time is one of the key aspects considered by Harwood et al. (2010), which is at the base of the SafetyAnalyst tool.

It is important to stress that this framework is flexible enough to be used in accordance with the objectives of the highway managing agency. In fact, the goal of safety interventions could be different: the main purpose could be achieving the “vision zero” in terms of fatalities and severe injuries (Stark et al., 2019), just reducing the fatalities (Gargett et al. 2011) or being focused on total crashes. According to the Vision zero target, for instance, Fleisher et al. (2016) tried to build the matrix of all the possible countermeasures and to distinguish them into layers. They identified three categories: measures with widespread adoption, limited implementation, and minimal utilization, which could be useful to understand which type of safety intervention could be selected. Such analyses could be integrated with the proposed framework, which includes budget constraints and an overall vision on the road network, to produce an optimized list of safety interventions in light of a Vision zero strategy. The same flexibility exists even if different crash types are considered instead of different severity levels. For example, Safaei et al. (2021) used also fuzzy techniques to prioritize interventions aimed to specifically reduce motorcycle crashes. Though, in this case, as well as Byaruhanga and Evdorides (2021) highlighted in their extensive literature review, budget constraints were not considered. The framework proposed here could be also used to prioritize interventions on a given road network, by focusing on a specific crash type.

5. Conclusions

In this study, an integrated multi-layer framework was proposed, which includes the typical problems of the network safety management (estimating safety performances, identifying hotspots, defining possible safety measures and estimating their effects, prioritizing interventions under budget constraints) into a single optimization procedure. This procedure provides the number and type of safety interventions to be implemented over a wide road network composed of different categories of road elements. The underlying method is based on the following key aspects: the potential for safety improvement is separately estimated for each road category based on safety performance functions, a bi-level thresholding process (a fixed frequency threshold and a threshold variable with the traffic volume) is used to highlight sites for interventions, the anticipated outcome of safety measures is quantitatively assessed through crash reduction factors.

The applicability of the proposed framework was demonstrated through a case study, in which a sample road network composed of 145 road sites (belonging to different segment and intersection categories) was considered. It was shown how, depending on the different budget scenarios, sites belonging to various road categories are prioritized, by relying on different possible combinations of safety measures.

Clearly, the proposed methodology is not without limitations. As anticipated in the introduction section, it is a multi-layer approach, from the screening of safety performances to the selection of countermeasures, considering economic boundaries. It has the advantage of condensing several aspects into a single simple procedure based on a unique optimization process. On the other hand, all layers of analysis necessarily rely on a set of assumptions. In particular, the site selection process is based on a bi-level thresholding process which follows practical considerations. Moreover, the selection of countermeasures is simplified because the optimization procedure should be conducted at the higher level of a planning stage. However, the planning stage necessarily requires some assumptions since several variables, which are usually collected at the project stage, are still unknown. Hence, the proposed framework is deemed as a trade-off between the need of treating in detail several aspects of the safety prioritization process and the need for a straightforward procedure which can be used in practice with the least amount of available data.

Nevertheless, the proposed framework is flexible enough to be implemented with additional data which may be available to highway managing agencies. For example, the alternative countermeasure types may be specifically selected for groups of road sites, once the diagnosis of safety problems is conducted at different levels of detail. At the same time, costs of countermeasures can be determined as based on local real projects, taking into account maintenance costs (see e.g., Martensen et al., 2018). In fact, results presented in this article are valid for the specific sample dataset used and they may also significantly vary once input data are changed.

CRediT authorship contribution statement

Paolo Intini: Conceptualization, Methodology, Software, Formal analysis, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Nicola Berloco:** Conceptualization, Methodology, Writing – review & editing. **Stefano Coropulis:** Data curation, Visualization, Writing – original draft, Writing – review & editing. **Vittorio Ranieri:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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