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Integrated American-European protocol for safety interventions on existing two-lane rural roads

Pasquale Colonna[1] · Paolo Intini[1] · Nicola Berloco[1] · Vittorio Ranieri[1]

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Abstract

Purpose The main purpose was to integrate two strategies for road safety analyses (qualitative: audits, inspections; and quantitative: accident predictions) and develop a possible protocol for the safety interventions on existing two-lane rural road segments. Those road sections do not typically belong to the TEN-network, to which the 2008/96/EC Directive is mainly oriented. Hence, they could lack of methods for designing safety-based interventions. The main research questions were:

- Which possible problems can arise from the application of this protocol to real cases?
- Which data are practically needed?
- Which possible solutions can be provided for the highlighted problems?

Methods The integrated protocol, including: 1) the HSM predictive method, 2) the EU Regulations, 3) the local road design standards, 4) some research developments; is applied to real two-lane rural road segments requiring safety-based interventions. Its application is divided in the typical road safety analysis stages.

Results A wide list of possible problems was highlighted and addressed: 1) lack of data, 2) difficult comparison with current road standards in order to identify safety problems, 3) lack of methods for evaluating the skidding risk along the layout, 4) setting speed limits, 5) need for optimizing the selection of countermeasures based on their aims and their timely application, in different recurrent situations, 6) availability and comparison of predictive methods.

Conclusions Based on the problems and solutions discussed, main advantages (1) the systematic approach, 2) the quantitative assessment of benefits, 3) the possible transferability) and disadvantages (difficulties in overcoming the lack of data and calibrated accident prediction models) of the method were remarked.

Keywords Safety interventions · Existing roads · Two-lane rural road segments · Highway safety Manual · Directive 2008/96/EC

1 Introduction

Roads should not only guarantee mobility performances, but also, and most importantly, be safe. Some States such as Sweden [1], and entire communities [2], have set ambitious goals for reducing road accidents and their consequences. Reaching these goals highly depends on international research, since it contributes to develop and update manuals, guidelines, National and International standards [3–8].

From a road design perspective, the aim of reducing crashes on existing roads may be pursued by identifying sites needing intervention, and by improving road safety on these sites. For both these two activities, quantitative estimates for assessing and comparing accident frequencies and safety benefits of alternative countermeasures may be needed. The introduction and development of Safety Performance Functions (SPFs)/Accident Prediction Models (APMs), aimed at predicting the accident frequency based on a list of variables (see e.g. [9] for an early study); and of Crash Modification Factors (CMFs), aimed at quantifying the effect of road measures on the crash frequency (see [10, 11]); can be considered as milestones for quantitative predictions.

✉ Pasquale Colonna
pasquale.colonna@poliba.it

✉ Paolo Intini
paolo.intini@poliba.it

[1] Technical University of Bari, 4 via Orabona, 70125 Bari, Italy

However, there is no universal consensus on a method for designing safety interventions, from the diagnosis stage to the evaluation of countermeasures. In this sense, approaches are different and may also include, or be exclusively based on qualitative assessments, besides of quantitative predictions. An overview of different possible approaches: the quantitative approach proposed in the Highway Safety Manual [6]; the mixed approach of Australian National Risk Assessment Model (ANRAM) [7]; and the mainly qualitative approach proposed by the EU Directive 2008/96/EC [12] transferred, eventually with modifications, to European member States; is presented in next sections.

1.1 Approach used in the highway safety manual (HSM)

The HSM provides a detailed method for estimating the mean accident frequency (considering total accidents, or specific types/severity) for a given period and according to: traffic volumes, geometric and traffic control features.

The estimates for each site inquired, either a homogeneous road segment (urban/rural, divided/undivided, two-lane/multilane) or intersection (signalized/un-signalized), are based on a predictive method composed by:

- Safety Performance Functions (SPFs): regression models, able to estimate the mean accident frequency of a given road infrastructure type for a set of base conditions, based on data related to similar sites;
- Crash Modification Factors (CMFs): representing the impact on safety of different road features (greater than 1 if the road attribute increases crash occurrence, and vice versa). The base accident frequency predicted by SPFs is multiplied by CMFs for accounting differences between base and site-specific conditions;
- Calibration Factor (Cx): factor multiplied to the mean accident frequency predicted by the SPFs for considering both the differences between jurisdictions and the periods of SPF development and application.

In detail, the HSM two-lane rural road SPF is based on an early study by Vogt and Bared [13] who used data belonging to several road segments in Minnesota and Washington States, and different predictors. The relations for applying CMFs to that SPF were developed by Harwood et al. [14], who collected previous studies relating crashes and features such as lane and shoulder widths [15–17] or curves [17, 18]. Details about HSM CMFs can be found in [19].

The overall prediction of the average accident frequency is based on the following equation:

$$N_{predicted\,x} = N_{spf\,x} \cdot (CMF_{1x} \cdot CMF_{2x} \cdot \dots \cdot CMF_{nx}) \cdot C_x \qquad (1)$$

where:

$N_{predicted\ x}$ = predicted average accident frequency at a given site x (accidents/year);

$N_{spf\ x}$ = predicted average accident frequency for the site x by appropriate SPF (accidents/year);

CMF_{1x} ... CMF_{nx} = crash modification factors, for a given site x;

C_x = calibration factor, in order to take into account the local conditions of the site x.

The $N_{predicted}$ can be combined with the mean observed accident frequency $N_{observed}$, through the Empirical Bayesian (EB) method [20]. This could reduce the regression-to-the-mean error, typically present in short period-based predictions (1–3 years). The output is the $N_{expected}$, a more reliable estimate of the long-term mean accident frequency, which can be used for future periods considering road/traffic changes. The EB method is applied through the equation:

$$N_{expected\ x} = N_{predicted\ x} \cdot \mathrm{w} + N_{observed\ x} \cdot (1 - \mathrm{w}) \qquad (2)$$

where:

$N_{expected\ x}$ = estimate of expected average accident frequency at a given site x for the study period;

$N_{predicted\ x}$ = predicted average accidents at a given site x (Eq. 1), computed over the study period;

$N_{observed\ x}$ = observed average accident frequency at a given site x, over the study period;

w= weight factor, depending on the reliability of the predictive model (over-dispersion parameter k).

The EB method can be applied at the site-level if the available observed accident data can be precisely located.

1.2 Approach used in the Australian National Risk Assessment Model

The HSM approach was targeted as a robust benchmark for detecting crash risk on the Australian network. Hence, local SPFs for fatal/serious injury crashes were developed. In addition, local and international CMFs can be considered, if relevant. At the same time, the existing AusRAP risk algorithms [7, 21] were assessed as valuable methods for identifying crash risk and then applicable as well. These algorithms put together several previously developed CMFs for different road attributes, by allowing their application to any road location.

The AusRAP approach is based on the combination of local CMFs related to three vehicle crash types (run-off-road; head-on; intersection-related). AusRAP refers to these CMFs for each crash type as Star Rating Scores (SRSs), related to road infrastructure, speeds and traffic levels. Summing up the partial crash type SRSs scores, the total SRS, a numerical value representing the relative severe crash likelihood for each 100 m road segment, is obtained. A similar procedure is proposed in iRAP (http://www.irap.org/en/about-irap-3/

methodology). The average SRSs values refer to the whole road section and than they are divided by the Australian network-wide SRS averages for each crash and road type, in order to obtain a specific crash-type weighting factor. This factor is equivalent to a HSM CMF for an individual road section given its features, speeds and potential conflicts.

Therefore, even if the predictive method used in the ANRAM is based on SPFs [22], the use of CMFs in the ANRAM approach differs from the HSM method.

Furthermore, even if using the HSM-like EB approach for the expected accident frequency, the Australian method uses an alternative method for computing the over-dispersion parameter (among the possible methods, see e.g. [23]), used for the calculation of the weight factor in Eq. 2. Finally, the ANRAM model, as the HSM procedure, is used to model future benefits of road safety programs, by estimating crash reductions, and Benefit Cost Ratios (BCRs) at different levels.

1.3 Approach of the EU regulations concerning road safety management

The EU Directive 2008/96/EC on the road safety management, aims to improve the level of safety of roads belonging to the Trans European Road Network TEN, through the introduction of safety enhancement procedures in the planning, design, implementation, management phases. It has been transposed into national laws by European countries. Some of them promoted National Implementing Measures (such as Germany, Lithuania, Czech Republic).

The procedures provided by the Directive are divided into four main categories, for different project stages:

- Impact Assessments (Planning Stage). Evaluation of the impact on road safety resulting from a new infrastructure project or from enhancements of existing roads (crucial for the approval stages of the project).
- Audits (Design Stage). Road safety checks concurrent with the design stage of a new infrastructure project or from enhancements of existing roads. Recommendations should be provided to avoid safety issues.
- Ranking and Management (Management Stage). Individuation of sites with potential for safety improvements, through the classification of the road network.
- Inspections (Management Stage). Identification of safety issues, to prioritize sites for future interventions.

In this article, the safety-based interventions on existing roads are examined. Therefore, the level considered is essentially the design stage. Anyway, as explained later, inspections can be integrated in the proposed protocol.

The Directive is applied to TEN roads, mainly multi-lane arterial roads. Its use for minor roads is encouraged but not mandatory, and the application schedule is locally variable. For example, in Italy, the Directive has been transposed into legislative decree in 2011 [24] and into National Guidelines in 2012 [25]. It should be applied to TEN roads, and after 2016, to secondary road networks. However, the Directive does not indicate clear methods for quantifying both safety problems and possible countermeasure-related benefits. In detail, SPFs are not explicitly recommended. This is a crucial matter, since they could be potentially integrated in assessments, audits, rankings. Therefore, for EU countries (for example Italy), local Regulations should be integrated with other methods, providing quantitative road safety performance indications.

1.4 Transferability of predictive methods

As explained for EU Regulations, road safety approaches may not include or rely on provisions/guidelines concerning quantitative crash prediction techniques. Hence, while the compliance with jurisdiction-specific regulations is necessary, the use of SPFs and/or CMFs locally available or developed in other contexts may be relevant.

SPFs are developed as single multi-variable models, or as (HSM-like) combination of base SPFs for standard configurations and a set of CMFs to account for differences between base and site-specific conditions [26]. Calibration factors may be used to account for differences between jurisdictions and application time periods.

Previous international research attempted to define SPFs, for different road and crash types, using a combination of exposure, road and context variables: see e.g. [27–30], for rural two-lane European roads (based on German, Italian and Portuguese segments); [31] for rural Italian motorways; [32] for signalized intersections in Canada; [33] for motorcycle crashes on Malaysian primary roads; [34] for bicycle accidents in the US. An important source of SPFs for different areas and road types, is the online repository of the EU Project PRACT [35].

The availability of detailed, high-quality data is crucial for SPFs development, while their formation and evaluation may be composed of several steps and rely on statistical techniques and physical significance [36–40]. Previous suitable SPFs may be not available in specific areas and their development may be unfeasible, especially for practitioners. The evaluation of time and costs needed for local studies producing reliable results should be considered among the transferability issues indeed [41]. If they are not acceptable, transferring SPFs or specific CMFs developed in other contexts to given jurisdictions should be needed, by relying on calibration or transferability assessments.

Previous research has examined several transferability issues. In particular, the HSM predictive method was assumed as a benchmark by several studies, which calibrated it for different areas [42–48]. Some of them clearly concluded that locally-derived functions fits better data than the calibration of other functions.

Other studies analysed the transferability of CMFs, such as the study by Yannis et al. [26], which provided transferability rankings for different factors, or by Elvik [49], which showed that horizontal curves-related accident modification functions developed in ten countries are significantly different. He proposed that average functions could be a representative summary of these models. Open sources of CMFs for several different safety measures are: the FHWA CMF Clearinghouse [50], the iRAP Road Safety Toolkit [51], and the PRACT repository [35].

1.5 Objectives and research questions

Most researchers focused on the development of statistically accurate models, having acceptable predictive capabilities, and based on enough reliable available data. These models could be the most suitable methods for predicting road crash risks, in a given area/region, under given boundary conditions. Other researchers focused on the transferability of these models in other contexts, which depends on their accurate calibration to local conditions.

However, practitioners who should design safety-based interventions on existing roads, including the processes of detecting safety issues, selecting and design countermeasures, assess their impact on safety performances, should address two concurrent matters. On one hand, they should abide to local regulations for the road design process and the road safety management, if relevant. On the other hand, they may need to rely on international (or anyway not local) tools for the crucial aim of quantifying safety performances. However, the path tending to the equilibrium and convergence between these two objectives may encounter several practical problems. Thus, the detailed analysis of the design process of road safety-based interventions in a local context may be useful, by considering the most relevant methodological problems, and trying to address them from a research-driven perspective. In fact, while research is broadly developed in several road safety aspects related to the inquired process, applied research on the development/application of overall design methods itself to local conditions, is scarce. The ANRAM procedure, based on the HSM methodology and applied to local conditions, is an example in this sense.

For this reason, in this article, a possible operational protocol for road safety interventions on existing two-lane rural roads implementing the Highway Safety Manual, the EU Regulations, local standards and research contributions, is proposed. It represents an attempt to include the advantages of different approaches by considering practical matters.

It is limited only to two-way two-lane rural roads. They were firstly selected, since they usually are the most widespread category in the existing network, and they could have been designed by following old standards, obsolete or no safety criteria. Moreover, the EU Directive may be not applied to minor roads, and general standards on how to define safety problems and measures could be not available. Hence, a method for the identification of safety problems and the quantification of costs and benefits for reducing road accidents, may be essential on these roads too.

The main research questions addressed in this article are:

- Which possible problems can arise from the application of the proposed method to real cases?
- Which data are practically needed?
- Which possible solutions can be provided for the highlighted problems?

The answers to those questions are based on the application of the proposed method to some two-lane rural road segments in the Puglia Region secondary network (Italy), which show high accident frequencies. Results were also compared with other similar tools currently available in the Italian context, namely the SPFs developed by Cafiso et al. [28], and Russo et al. [30] by highlighting possible differences and transferability issues. Anyway, the proposed method could be applicable in all the contexts where local data and studies are lacking; and where practitioners face the practical problem of assessing safety performances and improvements at specific sites. Moreover, the proposed method also introduces some novel elements, besides of being a potential operating framework for different contexts.

The remainder of the paper is structured as follows. Next section 2 is devoted to the explanation of the proposed protocol for designing interventions on existing two-lane rural roads. Then, the application of the method to real cases is shown in Section 3, focusing on the possible problems and solutions. Among the pilot applicative projects performed, some examples including most of the common key problems encountered on two-lane rural segments were chosen. Finally, conclusions about the main advantages and disadvantages of the method are drawn in Section 4.

2 Integrated operational protocol for safety interventions on existing two-lane rural road segments

In this section, the proposed integrated operational protocol is presented [52]. Although the implementation of predictive methods could be of more interest for the European countries, the operational approach of the method includes some practical matters potentially of interest independently from the specific country or region. The road safety management scheme provided by the HSM and the PIARC Road Safety Manual is used. Starting from the end of network screening, it includes:

diagnosis, countermeasures selection, and choice among possible projects.

2.1 End of network screening stage

In this article, focused on safety-based intervention design, it is assumed that a network screening already occurred in a given jurisdiction and that some sites were marked as candidates for safety interventions. The problem is that the screening could have been conducted by considering incomplete safety performance indicators (i.e. only accident frequencies, if enough data were not available). In this sense, for example, Italian Regulations based on the EU Directive 2008/98/EC suggest the Safety Potential (SAPO), an economical performance indicator relying on accident rates and average accident social costs, while predictive methods are not explicitly provided. Anyway, independently from the reasons why a road site was selected for safety-based interventions after the screening, the designers of the interventions are interested in knowing its actual safety level. This information can be crucial in order to: 1) know the potential for safety improvements, 2) ponder the type of interventions, 3) make comparisons with similar sites.

2.1.1 Proposed methods for verifying the level of safety of the site

A useful tool for this aim could be the Level of Service of Safety (LOSS) method [53], included in the performance indicators provided by the HSM. The LOSS is a qualitative measure for defining the safety level of a road site, with regard to its predicted performance. If a road type-specific SPF is available (see Fig. 1), the predicted average accident frequency for a given AADT could be a reference measure for the safety level. The deviation from this value can be used for defining different levels of service. The curves delimiting the areas corresponding to the different levels can be placed [54] at a distance corresponding to given percentiles of a gamma-distribution (or standard deviations from the mean in the first version). Four LOSS are so identified (Fig. 1). If a road site experienced crash frequencies higher than the SPF prediction, than it can be marked as less safe.

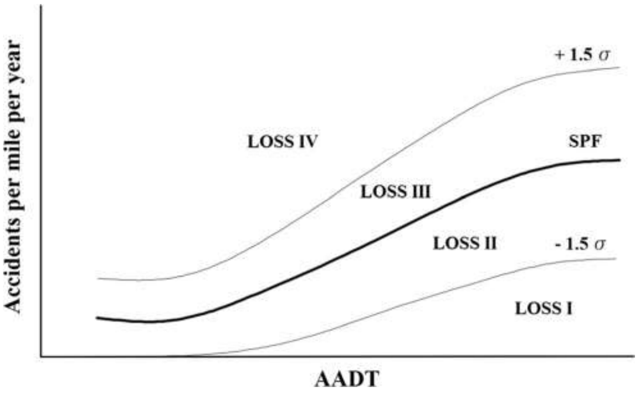


Fig. 1 Definition of the Level of Service of Safety measure, based on [53]

Therefore, practitioners, before designing the safety interventions can apply the LOSS method for the aim of knowing the actual safety level of that site. This stage could be essential to know its potential for safety improvement.

2.1.2 Data need

- Data about the observed accidents at the site for at least the more recent three years;
- An already developed Safety Performance Function of reference for two-lane rural roads;
- A calibration factor for that SPF in the specific jurisdiction (see Eq. 1);
- Traffic volumes.

2.2 Diagnosis

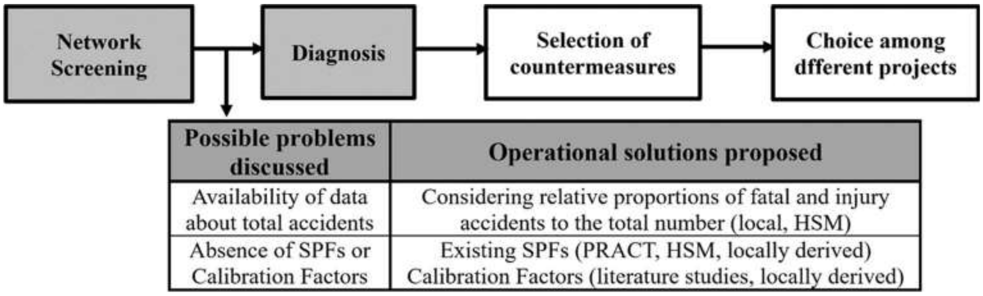
After the level of safety of the site is known, the diagnosis of problems can start. The subsequent steps are proposed.

2.2.1 Proposed methods for diagnosis

Reconstruction of road geometry The diagnosis of the existing road site necessarily starts from the reconstruction of the road alignment. CAD/GIS elaborations could be necessary for accurate digital terrain and elevation models.

Individuation of homogeneous road segments Once the alignments are defined, the road site can be divided into homogeneous segments. In this sense, both the HSM and EU Guidelines give some indications. The different combinations of horizontal and vertical alignments and changes in the geometric standards between different sections (e.g. change in the lane width) have to be considered. A minimum length of about 160 m (0.1 ft) is set by the HSM.

Reconstruction of the accident history Accident history is necessary to reconstruct the possible accident patterns at the investigated road site and to individuate possible points at which accidents are clustered. Useful tools for visually identifying crash clusters and patterns, otherwise potentially not evident by only looking at crash statistics, are the collision diagrams. They are two-dimensional plan representations of the crashes occurred at a site within a given time period. Vehicles involved are represented in the diagrams through arrows indicating the accident type and dynamics. Other information can be provided near to each symbol (e.g.: severity, date, hour, weather, lighting, etc., see HSM).



Possible problems discussed	Operational solutions proposed
Availability of data about total accidents	Considering relative proportions of fatal and injury accidents to the total number (local, HSM)
Absence of SPFs or Calibration Factors	Existing SPFs (PRACT, HSM, locally derived) Calibration Factors (literature studies, locally derived)

Fig. 2 Intermediate stage between screening and diagnosis. Problems and solutions

Comparison between the existing situation and the actual standards Each State adopts its own regulations regarding road design standards. Anyway, road standards which numerically can differ from one country to another, are usually based on some common rules including safety-based concepts accepted worldwide (i.e.: road geometric consistency, minimum curve radius, spiral transition curves, available sight distance, road friction to guarantee, homogeneity of speeds, etc.). Comparing the existing situation with the standards set for that type of road (e.g. lane and shoulder width, number of lanes) and for that road layout (all the safety-based checks) could be useful in understanding where the problems lie, besides of other diagnosis outputs. In other words, the road design safety checks considered by local Regulations for preventing safety problems could be applied on existing roads for identifying possible problems.

Evaluation of the skidding risk Roadway departure crashes (typically single vehicle run-off-road accidents) are responsible for 53% of road fatalities in the United States [55]. Road friction plays a fundamental role in determining the skidding risk. Anyway, currently, no detailed safety checks are required for road friction along a road layout. Usually, some global checks concerning road friction are required by regulations, e.g. based on the work by Lamm et al. [56]. Global checks do not normally consider the influence of different vehicles, boundary conditions, specific road sections (combinations of road elements belonging to both the horizontal and vertical alignments). A possible method for: 1) computing the friction used by a given vehicle in a specific road section under some boundary conditions and, 2) comparing it with the available friction, is the Friction Diagram Method [57]. The output of the proposed method is a diagram giving for each section the comparison between the Friction Demand (F_D - friction needed by the vehicle for not skidding) and the Friction Potential (F_P) that the road geometry can provide given the boundary conditions. The ratio between the Friction Demand and Potential is defined as Friction Used (F_{USED}):

$$F_{USED} = \frac{F_D}{F_P} \cdot 100\ (\%) \tag{3}$$

If the F_D exceeds the F_P, resulting in a F_{USED} greater than 100%, safe driving conditions are not ensured. Hence, an intervention is needed for the specific road segment to address the possible skidding risk. The Friction Diagram is the graphical depiction of the F_{USED} along the road, useful to identify where the problems lie (see the example in Section 3). The Friction Diagram can be referred to different vehicles but, the critical vehicle showing the worst skidding performance for each section can be usefully defined. Several variables were implemented in the model considering: road design (combinations of horizontal/vertical road elements), vehicle features (e.g. wheelbase, front track, height of the center of gravity), vehicle dynamics (acceleration, deceleration) and environmental conditions. The application of the proposed method can be helpful during the diagnosis for identifying possible friction issues on the existing road.

Road inspection Inspections are useful tools for identifying safety issues on site. In the HSM, some indications are included in the methodology for diagnosis. Whereas, for example, in the Italian Guidelines [25] attached to the Regulations obtained by transposition of the EU Directive, an operational method for conducting road inspections is given. Indications about all the road-related parameters to consider (traffic, signs, posted speed, drainage, visibility, etc.) are given too (Table 1). Qualitative judgments are provided by the inspectors (road safety experts) for each parameter, indicating the danger level. Precise guidelines for inspections are given, regarding the time of the day (day-time and night-time inspection), the inspection type (preliminary, scattered, punctual, with different levels of detail) and the travel speed during them. A similar precise and locally available protocol for road inspections can be very useful also for the diagnosis process explained in this section. Moreover, inspections should be conducted when the stages of reconstruction of road geometry and accidents, and the comparison with standards have already occurred. Thus, punctual inspections may be focused on already highlighted problems.

Reconstruction of boundary conditions Once all the road-related safety features have been identifyed and the inspection has been conducted, an overview of the boundary conditions

Table 1 Part of a preliminary road inspection sheet (adapted from [25])

Macro-area	Item	Parameter	Indicator	Judgement (to be filled by the road inspector)
General features	CRITICAL WEATHER CONDITIONS	WEATHER (fog, wind, snow, rain)	Lack or insufficient advices to users	√
			Inadequate countermeasures	√
		ROAD PAVEMENT CONDITIONS (ice, water flooding, rubbles)	Lack or insufficient advices to users	√
			Inadequate countermeasures	√
	TRAFFIC	VOLUME	Inadequate cross-section	√
		TYPE	Presence of specific components	√
	SURROUNDING ENVIRONMENT	CLEAR ZONES	Presence of obstacles, dangers, service roads, etc.	√
		CLEAR ZONES (OUT OF THE FENCES)	Presence of buildings, trees, etc	√
		BEYOND CLEAR ZONES	Distraction for particular problems, other roads, etc.	√
	SPEED	DESIGN SPEED - OPERATING SPEED	Excessive difference (+/−)	√
		MAXIMUM POSTED SPEED - OPERATING SPEED	Excessive difference (+/−)	√
	ROAD SIGNS	HORIZONTAL ROAD SIGNS	Not homogeneous	√
		VERTICAL ROAD SIGNS	Not homogeneous	√
		VARIABLE MESSAGE SIGNS	Ineffective information	√
Geometry	HORIZONTAL ALIGNMENT	TANGENTS	Excessive lengths	√
		TRANSITION CURVES	Absence or Inadequate transition curves	√
		CIRCOLAR CURVES	Inadequate radius of curvature	√
	VERTICAL ALIGNMENT	SLOPES	Excessive slopes	√
			Excessive lengths	√
		CREST VERTICAL CURVES	Presence of crest vertical curves	√
		SAG VERTICAL CURVES	Presence of sag vertical curves	√
	PERCEPTION	PERCEPTION	Incorrect sight perception	√
			Losing perception of road layout	√

for the specific site is built. The existing conditions can be graphically depicted on a diagram overlaid on the horizontal alignment. This diagram illustrates all the boundary elements such as, for two-lane rural roads: retaining walls, trees, signs, posted speed, lighting, potholes, surface irregularities, vegetation in drainage elements and all the other elements of interest for the safety analyst.

Consideration of human factors While designing interventions on existing roads, it should be always taken into account that human factors are the most important contributor to accident occurring. In fact, recent statistics [58] estimate that more than 90% of crash critical reasons are driver-related, while the environment-related (including the road) are less than 5%. However, all factors (driver, vehicle, road, traffic and environment) interact with each other in the process of accident occurring [59]. Therefore, even if the critical reason can be almost always attributed to drivers, the percentage of accidents in which road played an important role in the chain of events is higher than 5% [60]. Anyway, road-related features can be easily measured and compared with standards, while possible driver-related features are not easily measurable as well. Considering to adapt to standards a given road should result in the compliance with some safety-based criteria integrated in new design and behaviour-related standards (i.e.: parameters of tangents and curves are ruled by road consistency). However, there are several features not considered by design criteria, such as the drivers' familiarity with a given route. The latter was found to be related to a significant increase of speed for familiar drivers, roughly independent from road geometry, but more dependent on personal attitudes [61–63]. Therefore, a tool for considering human factors related to accidents should be considered. The Haddon Matrix, useful for identifying crash contributing factors before, during and after the crash could be helpful for this aim. It should be built for each crash recorded on the segment with the aim of understanding all the possible contributing factors. Another important source is the work by Campbell et al. [64], providing guidelines for considering human factors in road design.

2.2.2 Data need

- Digital Terrain and Elevation Models of the inquired area and/or survey points;
- Data about the observed accidents at the site for at least the more recent three years;
- Accident reports;
- All the possible supplementary information about the boundary conditions.

2.3 Selection of countermeasures

The selection of countermeasures depends on the diagnosis outputs. Each safety problem should be addressed by an appropriate measure. Otherwise, a single measure producing a greater impact on safety can solve a group of problems.

This is the veritable project stage requiring engineering judgment, in which new features are designed. According to the EU Directive, this phase should include a safety audit, checking each project part from a safety perspective. However, this article simulates a project in which interventions are mainly safety-based. Hence, the discussion in this section (deriving from previous ones) can be considered as coherent with a road safety audit during the design stage.

2.3.1 Proposed methods for the selection of countermeasures

Once problems were identifyed during the diagnosis stage, appropriate countermeasures can be selected by considering their effect on safety. The quantification of this effect for different types of safety measures can be found in the HSM or also in other web sources [35, 50], where several CMFs are provided. Moreover, a systematic review of possible road safety measures can be found in Elvik et al. [4]. As previously stated, human factors play an important role in the accident occurring. To account for driver behaviour while selecting countermeasures, the Human Factors Guidelines for Road Systems [64] could be a valid help. Several road scenarios and interventions considering the possible behavioural influence are considered and proposed.

Sets of countermeasures The problems resulting from diagnosis could be several and various. This may lead to the selection of a huge number of possible countermeasures. However, if a group of countermeasures was selected for solving the same type of problem (e.g. the same recurrent crash type or crashes clustered at a particular segment), they can be considered together as a "set" of countermeasures rather than several single measures. Countermeasures can be also grouped by considering their timely application: short-term inexpensive safety measures giving small benefits, long-term expensive projects of road alignment reconfigurations giving high benefits, or interventions curing ordinary maintenance poorly done in the past. The authors believe that the strategy of grouping countermeasures according to both their aim and their timely application could simplify the computation and interpretation of cost-benefit analyses.

2.3.2 Data need

- Results from the diagnosis process;
- Details about possible countermeasures for a given problem.

2.4 Choice among different projects

At this stage, possible countermeasures (or sets of them) have been identified (1 to n). The final stage concerns the economic assessment, leading to choose between alternatives. The steps associated to this stage are listed as follows:

1. The expected average accident frequency $N_{expected}$ is computed for each homogeneous segment composing the road site (as it is before the intervention), by repeatedly applying Eqs. 1 and 2;
2. The $N_{expected}$ for the whole road section is obtained by summing values for each homogeneous segment;
3. For the i-esim countermeasure (or set), the procedures at points 1 and 2 are repeated considering the scenario after the implementation of the countermeasure;
4. For the i-esim countermeasure (or set), the difference between the $N_{expected}$ values before and after the implementation of the countermeasure is computed ($\Delta N_{expected}$);
5. The $\Delta N_{expected}$ associated to the i-esim countermeasure (or set) is multiplied by the accident average social cost (normally locally derivable). It is the monetary safety benefit associated to the i-esim measure (or set): B_i
6. The procedures at points 3 and 4 are repeated for all countermeasures (or sets) from 1 to n.
7. Assess the cost of implementation related to the i-esim countermeasure (or set): C_i;
8. Choose the project among all the possible i alternatives of countermeasures (or sets), by comparing the safety benefit B_i, with the cost C_i of each countermeasure, over all its life.

The stages from 1 to 6 are based on the HSM procedure, briefly recalled above. That procedure is normally separated for severity classes, since different severity social costs exist. For this stage, the same data described in 2.1 are needed. As previously explained, the most suitable alternative predictive methods are: a calibrated HSM SPF or a local SPF. The specific matter of choice between available predictive methods (locally derived or HSM-derived) and an example of comparison between outputs of different methods is addressed in next sub-section.

Concerning point 8, the HSM provides several possible techniques. However, it should be stressed that priorities could be potentially independent from cost-benefit analyses. For example, budget constraints or the priority for reducing fatal accidents [65], could allow the formation of different possible rankings.

The following measures are considered for conducting cost-benefit analyses in the application section:

$$\text{Net present value, NPV} = \sum_{y=0}^{Years} \frac{Safety\ benefit\ due\ to\ reduction\ in\ crashes_y}{(1+discount\ rate)^y}\ [monetary\ unit] \tag{4}$$

$$\text{Benefit–Cost Ratio,}\quad \text{BCR} = \frac{\text{Incremental Benefits over the years (discounted value)}}{\text{Incremental Costs over the years (discounted value)}} \tag{5}$$

The incremental cost-benefit analysis is also performed. It consists in listing all project alternatives in ascending cost order and then conducting all the possible pairwise comparisons by using the incremental BCR ratio (ratio between differential benefits and differential costs between the two projects) as reference measure. The winning alternative is defined at the end of all comparisons, by selecting step-by-step the introduced alternative providing a positive ratio.

2.5 Selection of alternative predictive methods

In order to simulate the decision between available alternative predictive methods and highlight the possible problems and transferability issues to specific contexts, different approaches are considered. For this aim, the SPFs developed for Italian rural two-lane roads by Cafiso et al. [28], as multi-variable equation; and by Russo et al. [30], as local base SPF and associated CMFs; were selected. The applicability and the results obtained through these methods were compared with the results and feasibility of a calibrated HSM SPF for local conditions [48].

The locally available models used are reported as follows:

$$N_{predicted\ (Cafiso\ et\ al.,2010)} = e^{-6.682} \cdot L \cdot AADT^{0.619} \cdot e^{0.0646DD-1.89CR+0.0691s} \tag{6}$$

$$N_{predicted\ (Russo\ et\ al.,2016)} = e^{-1.75} \cdot L \cdot 365 \cdot 10^{-6} \cdot AADT \cdot (CMF_{\mathrm{LW}} \cdot CMF_{\mathrm{CI}} \cdot CMF_{VG}) \cdot 0.68 \tag{7}$$

where:

DD = Driveway Density;

CR = Curvature Ratio, total curved portions within the homogeneous segment, divided by segment length;

s = standard deviation of operating speeds, computed for each portion composing the homogeneous segment;

LW = Lane Width;

CI = Curvature Indicator (based on the Curvature Change Ratio, deflection of the horizontal alignment);

VG = Vertical Grade.

Equation 6 was selected among the functions proposed in the study, since it includes several parameters, showing also acceptable goodness of fit indicators and statistical significance ($p < .05$) of all the parameters considered. Equation 7 was selected among the functions proposed in the study, since it predicts all casualties (fatal/injury accidents).

3 Application

Some examples of the procedure previously explained are shown in this section. The presentation of the examples (divided for the diverse stages, as in Section 2) is useful to highlight possible problems typically encountered. Some solutions will be suggested in order to address them.

In all stages from 3.1 to 3.4, the examples shown are taken from the same Pilot Project 1 (PP1). When necessary, examples from PP1 are integrated with examples from another pilot project: Pilot Project 2 (PP2). Both the two pilot projects were based on existing two-lane rural road sections 2 km long, in the Province of Bari, Puglia (Italy).

3.1 End of network screening stage

For the Pilot Project 1 (PP1), the following data were collected, related to the study period (2008–2014): AADT = 4202 vehicles/day; $N_{observed}$ = 14 accidents reported, 11 out of 14 were at least injury accidents.

In order to use the LOSS method [53] for knowing the actual safety level, the expected number of accidents should be computed. An appropriate two-lane rural road SPF and a Calibration factor (Cx) are needed.

The following problems were highlighted for the end of network screening stage: 3.1.A and 3.1.B. Solutions are proposed for both of them. These problems and solutions are generally applicable to other similar sites (Fig. 2).

Problem/solution 3.1.A The total number of accidents could be largely underestimated in PP1, since the fatal and injury (FI) accidents reported are almost 80% of the total number, while they are usually around 30% (32.1% according to [6]). This is a very common situation which can affect accident predictions [66]. Moreover, in most cases, *only data about fatal and injuries accidents* are obtained, but the appropriate SPF considers total accidents. In this case, before the application of the LOSS method, the number of available accidents should be adjusted by considering the relative proportion of FI accidents to the total number (locally derived values or, alternatively, HSM default values), see 3.1.B for detailed calculations. The average $N_{observed,\ FI}$ over the study period is equal to 11 acc./7 years = 1.57 acc. FI/y. The predicted number of accidents obtained by the SPF will be converted too into equivalent FI accidents for computing the $N_{expected}$ value through the EB method.

Problem/solution 3.1.B A SPF is needed. In order to apply the HSM predictive method, the base HSM SPF should be used, and adjusted through a Calibration factor Cx. If the *Calibration factor is not available*, there could be four possibilities: 1) Develop a new SPF, 2) Develop a Calibration factor, 3) Use the HSM base model, 4) Use a locally developed suitable SPF. The first two options are realistically unfeasible for practitioners, then the base or calibrated HSM model or other locally derived two-lane rural road SPFs (see e.g. PRACT Online repository [35]) may be applied as they are. In particular, for two-lane Italian rural roads, the authors provide some calibration factors (Table 2).

In the example of PP1, the average $N_{observed,\ FI}$ over the study period is: 1.57 acc. FI/year. By applying the HSM model (Eq. 1), with Cx = 1.24 (for low-volume roads of the Puglia region [48]), the $N_{predicted}$ is: 0.88 acc./y/km. The equivalent FI accidents can be computed, considering their share among the total (32.1%), and over all the section 2 km long: $N_{predicted,\ FI}$ = 0.57 acc. FI/y. By using Eq. 2, with w = 0.57 (depending on the over-dispersion k parameter of the SPF, segment length and predicted accidents), the resulting expected average accident frequency for the site PP1 is: $N_{expected,\ FI}$ = 1.00 acc. FI/y ($N_{expected,\ FI}$ = 0.50 acc. FI/y/km, equivalent total: $N_{expected}$ = 1.55 acc./y/km).

In Fig. 3, the updated LOSS framework [54] is applied to two-lane rural roads in the Puglia region. The red point represents the site PP1 (AADT = 4202; $N_{expected}$ = 1.55 acc./y/km). It belongs to the LOSS-IV, showing the highest potential for safety improvements, due to the high distance from the SPF. In this way, designers have quantitively estimated the safety potential for the site, and should ponder massive interventions due to high potential.

3.2 Diagnosis

This phase starts with the reconstruction of the geometric parameters of the existing roads. The geometric reconstruction of the site PP1 is reported in Fig. 4 (only the horizontal alignment is shown, but the vertical alignment was reconstructed too). Existing road geometric parameters are necessary for the comparison with actual standards.

The following problems have arisen during the diagnosis stage, based on the projects at sites PP1 and PP2: 3.2.A, 3.2.B, 3.2.C, and 3.2.D (see Fig. 5).

Problem/solution 3.2.A The *current road functional classification* may not correspond to the one valid when the road was designed. Thus, in order to conduct safety checks based on geometric features, the existing road should be assigned to a current class based on its features, but also its territorial function. In the example of site PP1, the road connects two towns (< 30,000 inhabitants) and it collects traffic from a main highway and a freeway. However, its cross-section standards correspond to an access/local road, a common condition for old-designed two-lane rural roads. In similar cases, the territorial function should be more important than actual road features, while assigning a category.

Problem/solution 3.2.B All safety checks are usually based on the *design speed*. However, the design speed used for the existing road project is not normally known. The problem could be solved by obtaining information about the old project (strategy generaly valid for the diagnosis process). This solution is normally unfeasible and three other strategies can be evaluated: 1) considering actual speed limits, 2) deduce design speeds through the reconstructed geometry, 3) consider the operating speeds (85th-percentile speeds). These alternatives are evaluated considering the example of the site PP1. In that

Table 2 Example of Calibration Factors (Italian two-lane rural road segments [48])

Variable	Calibration Factor Cx	No. of Segments	Coefficient of variation cv[Cx]
Overall	1.44	398	0.07
AADT <10,000	1.19	316	0.09
AADT = 10,000 ÷ 17,800	1.75	82	0.10
North Italy	1.66	112	0.19
Central-Southern Italy	1.29	286	0.08
Flat Terrain	1.49	161	0.08
Rolling Terrain	1.38	237	0.11

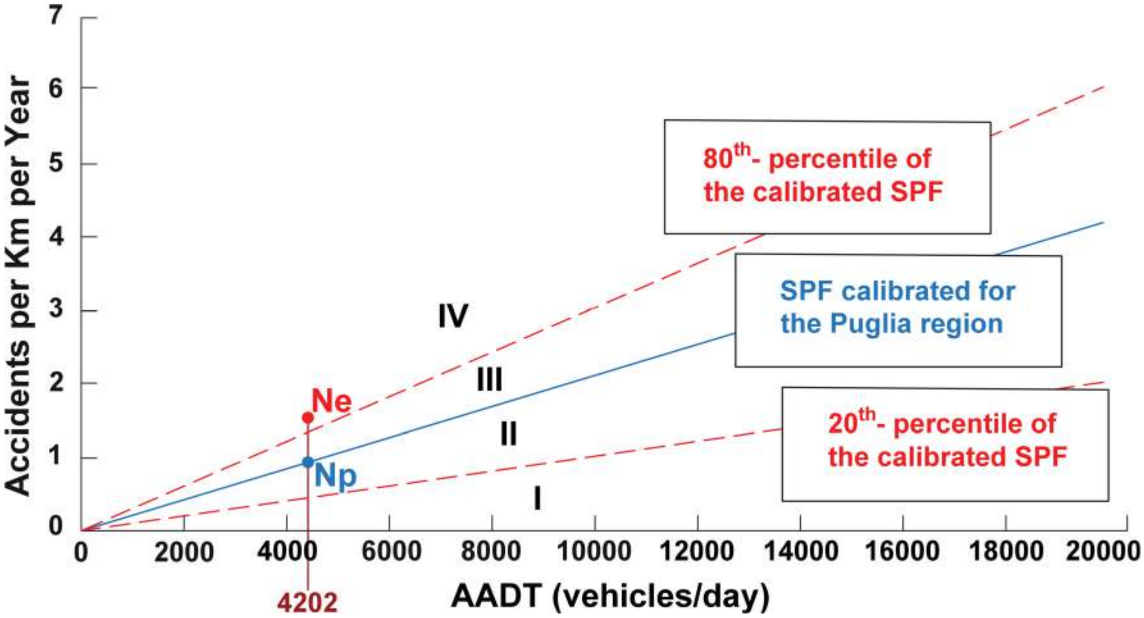


Fig. 3 Example of application of the LOSS measure for the site PP1 in the Puglia region (Cx = 1.24), Italy, belonging to the LOSS-IV (adapted from [52])

case, the following speeds were obtained: 85-th percentile speeds in most hours of the day notably higher than 100 km/h (even 130 km/h); speed limit at Tangent 1, in approaching at the subsequent curves set to 60 km/h; reconstructed design speed of 100 km/h at portions of Tangent 1 (about 6 km) far from curves, according to Italian standards. This can be a quite common situation on long tangents of low-volume rural roads, especially when speed cameras are not present. Hence, using posted speed limits for conducting safety checks during the diagnosis process could be dangerous. In fact, especially when road inspections (and/or operating speed data) highlight that the actual speed on the road is notably higher than the posted speed as in the case of site PP1, then the speed limit may be not abided by several drivers. Hence, it does not reflect the actual speed behaviour. In similar cases, searching for data regarding actual speeds at the specific site or using operating speed profiles for that section type in a given region [67, 68] is essential for setting an adequate speed for safety checks. If data about operating speeds are not available, then using the reconstructed design speed may be preferable.

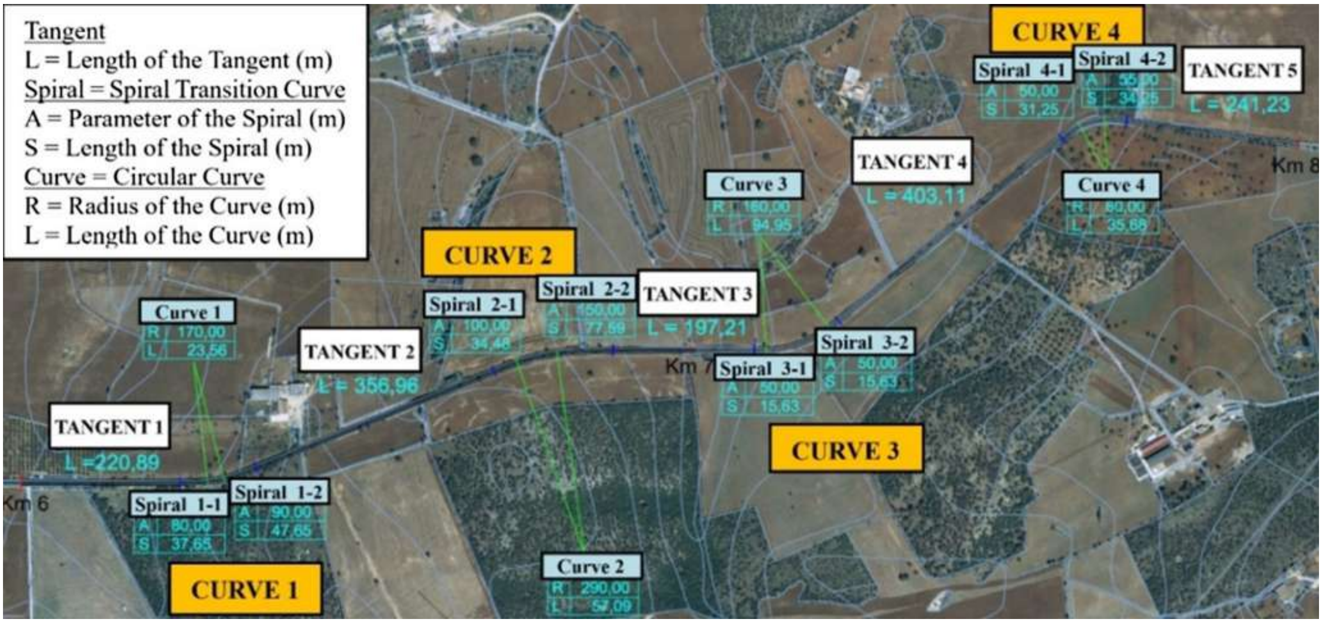
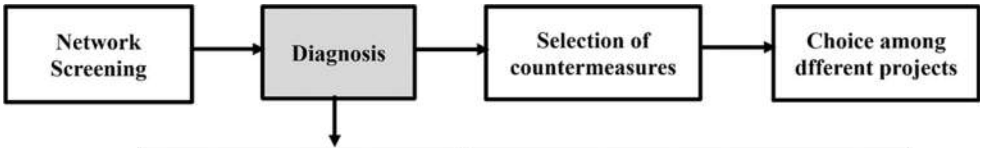


Fig. 4 Geometric reconstruction of site PP1 (horizontal alignment)



Possible problems discussed	Operational solutions proposed
Individuating the current road functional categories	Assign a road category based on the cross-section, but mostly on the territorial function
Select the speed to conduct the road safety checks	Reconstruct the design speed based on geometry, considering also posted and operating speeds
Presence of several driveways/minor intersections	Punctual visibility checks, in particular for high speed roads without traffic control
Determination of the role of friction in skidding risk	Use the proposed Friction Diagram Method

Fig. 5 Diagnosis stage. Problems and Solutions

Problem/solution 3.2.C The road site could be characterized by sharp curves and/or deteriorated road pavement (and/or high operating speeds). Site PP1 was an example of these sites (see Fig. 6). All these reported factors are related to lane departure crashes (typically single vehicle run-off crashes), in which *road friction* plays a crucial role. The possible risk of skidding along the road layout can be evaluated through the application of the Friction Diagram Method (FDM), as described in 2.2 [57]. The Friction Diagram of the site PP1 is reported in Fig. 7. Skidding is likely to happen in wet conditions at several sections ($F_{USED} > 100\%$). The FDM can reveal them for both design and diagnosis purposes. In this case, it is useful for quantifying the skidding risk and give indications about the sections at which a friction improvement is urgent. Moreover, since the available friction depends on speed, a speed had to be considered for each section composing the site PP1 while computing the F_{USED}. Based on 3.2.B, the reconstructed design speed was considered as reference variable for the friction analysis.

Problem/solution 3.2.D The road segment has *several driveways and/or minor intersections* (i.e.: intersection with minor access roads). Apart from specific regulations about the driveway density, visibility checks of driveways/minor intersections are essential, especially if collision diagrams and inspections highlighted particular driveway-related issues. This feature should be particularly addressed on roads characterized by high speeds (such as long tangents), without speed cameras and notable heavy vehicle traffic inducing passenger car drivers to dangerous overtaking manoeuvers. This is the case of site PP2 (2D overview in Fig. 8a). It is composed of a unique long tangent (about 4 km), connecting two towns (< 30,000 inhabitants) and characterized by several driveways/minor intersections (driveway density: 12.5 driveways/km).

As expected, several accidents cluster near driveways/minor intersections or they are related to them. The collision diagram related to a segment of site PP2 is reported in Fig. 8b. Moreover, the elevation profile (Fig. 8c) of the site PP2 shows

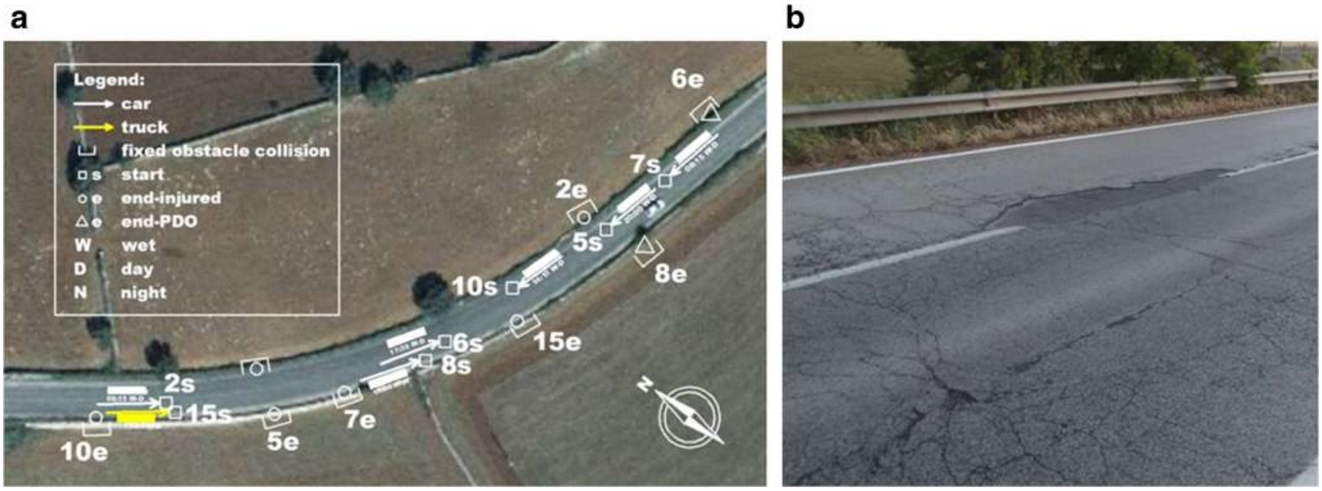


Fig. 6 Site PP1. **a** Collision Diagram of curve 3, **b** Example of deteriorated pavement along the road segment

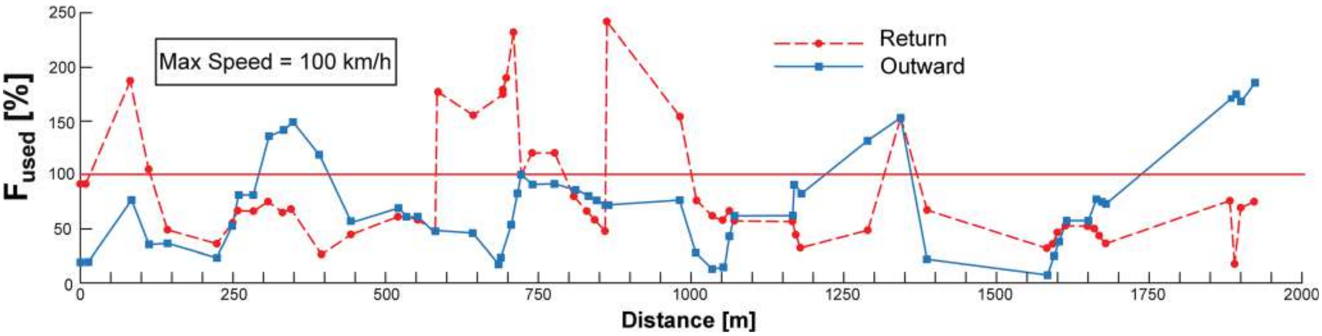


Fig. 7 Friction Diagram of Site PP1 in wet conditions (red line corresponding to $F_{USED} = 100\%$)

some steep grades (3–4%). The combination of the collision diagrams and the elevation profile requires particular attention for checking visibility of driveways/minor intersections, actually not ensured in several cases.

3.3 Selection of countermeasures

Once the diagnosis stage has been conducted, it is possible to select countermeasures. Based on the pilot experiences of the method application to several high-crash frequency two-lane rural sections of the Puglia region network, two main categories of problems can be highlighted for these types of roads. They are discussed in 3.3.A and 3.3.B. However, it is most likely that those two highlighted situations can be extended to more general National and International scenarios, being related to old roads built without complying with recent user-based design provisions.

The following problems have arisen during the selection of countermeasures stage, based on the projects at sites PP1 and PP2: 3.3.A, 3.3.B, 3.3.C, 3.3.D, and 3.3.E. The proposed solutions may be generally applicable to similar cases (Fig. 9).

Problem/solution 3.3.A The horizontal alignment of the two-lane rural road section is characterized by *long tangents allowing high speeds and sudden sharp curves* (eventually not provided with appropriate spiral transition curves or adequate speed reduction systems). Site PP1 is an example of this condition. Crashes are clustered at the curves after the long tangents (see e.g. Fig. 6a). Both the geometry reconstruction and the safety checks highlighted: inappropriate curve radii

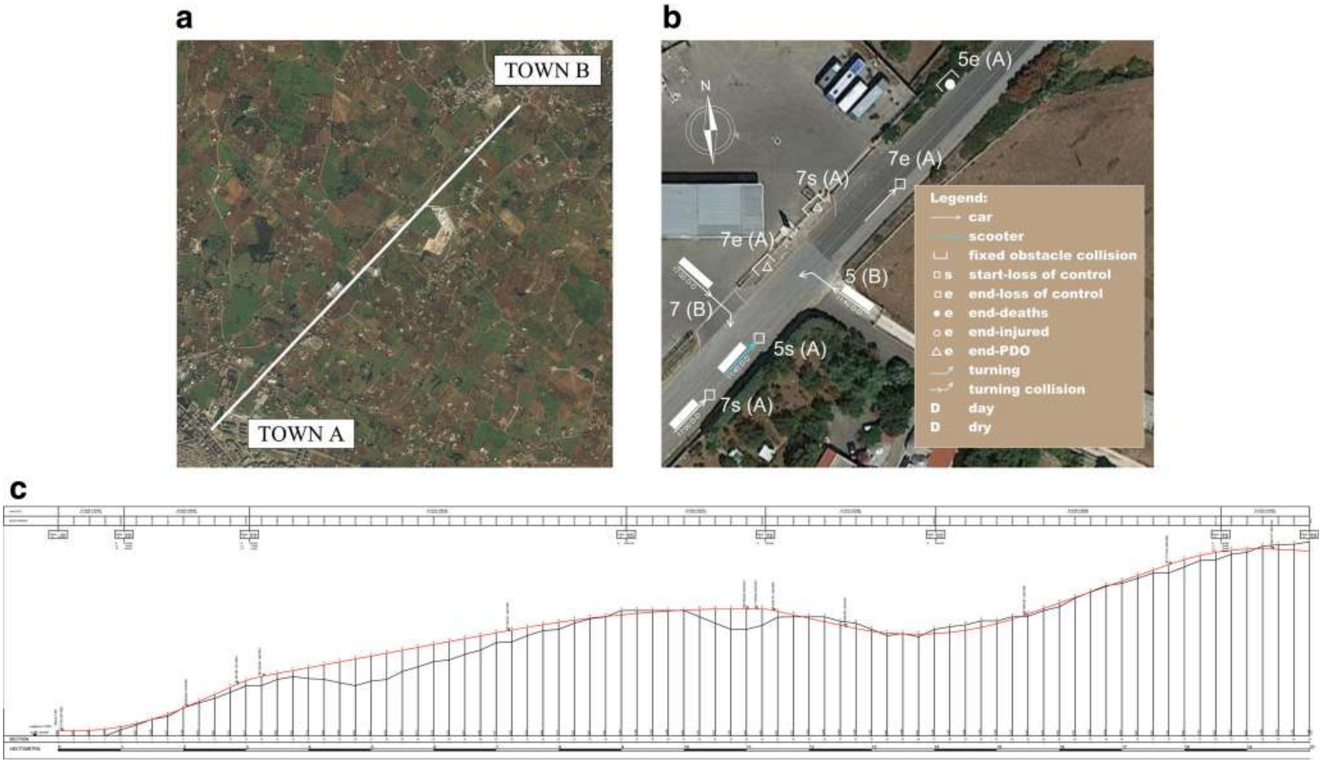
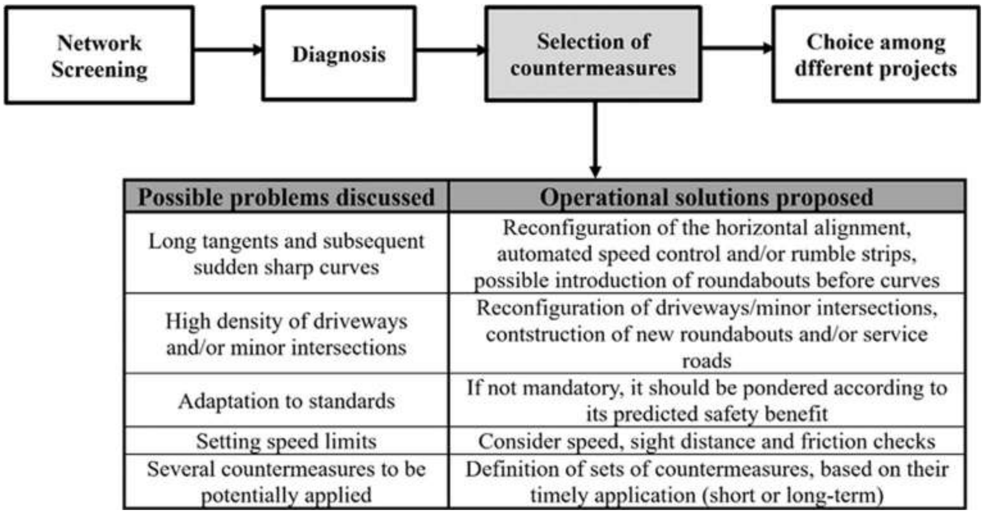


Fig. 8 Site PP2. **a** Overview, **b** Collision Diagram of a road stretch, **c** Elevation Profile



Possible problems discussed	Operational solutions proposed
Long tangents and subsequent sudden sharp curves	Reconfiguration of the horizontal alignment, automated speed control and/or rumble strips, possible introduction of roundabouts before curves
High density of driveways and/or minor intersections	Reconfiguration of driveways/minor intersections, contstruction of new roundabouts and/or service roads
Adaptation to standards	If not mandatory, it should be pondered according to its predicted safety benefit
Setting speed limits	Consider speed, sight distance and friction checks
Several countermeasures to be potentially applied	Definition of sets of countermeasures, based on their timely application (short or long-term)

Fig. 9 Selection of countermeasures stage. Problems and solutions

resulting in bad road consistency (Fig. 10a); actual high speeds while approaching curves; inappropriate vertical and horizontal alignment coordination. At site PP1, curve 3, steep grades are present before and after the curve, which is located in correspondence to a sag vertical curve. This can also result in bad drivers' perception of the actual curve radius (Fig. 10b). The most suitable solution could be the alignment reconfiguration, but it could be unfeasible due to environmental restrictions (i.e. protected areas) or other constraints (as for site PP1). In this case, speed reduction systems such as automated speed control and/or rumble strips should be considered. Otherwise, roundabouts may be placed at the end of long tangents in correspondence with minor intersections, before the sharp curves, to force drivers slowing down. Possible alternative projects considered (site PP1) are depicted in Fig. 11.

Problem/solution 3.3.B The two-lane rural section is characterized by a *very high density of driveways and/or minor intersections* and it allows high speed (i.e. it is a long tangent). Crashes are clustered at driveways and the safety checks highlighted that some of them are not visible and/or poorly designed and speeds are high (or there is a heavy vehicle traffic resulting in dangerous overtaking manoeuvers). Site PP2 is an example of this condition (Fig. 8). The more suitable measure may consists in a frontage road for collecting driveways. Anyway, for the reasons explained in 3.3.A, this could unfeasible. In this case, driveways could be eventually moved towards parallel secondary roads and/or short frontage roads may be designed where possible, to collect at least some driveways/minor intersections. If also these measures are

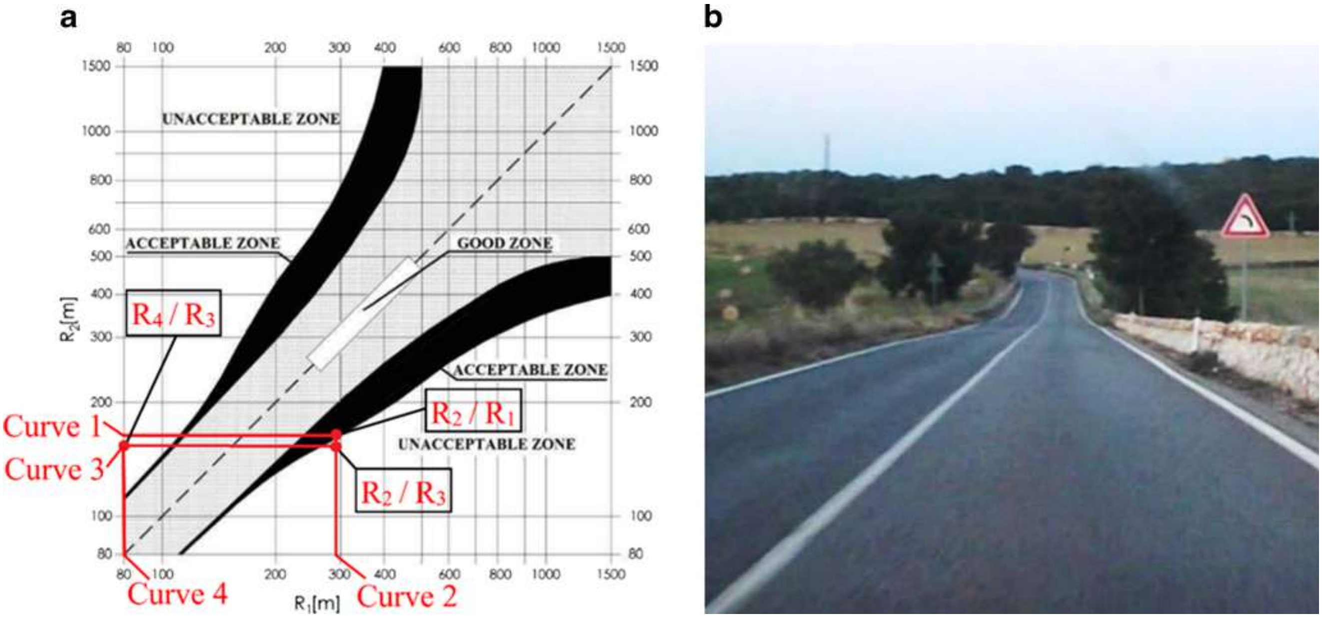


Fig. 10 Site PP1. **a** Bad consistency of the subsequent curves (1 to 4), based on the "Tulip" diagram in the Italian road standards. **b** Bad coordination of horizontal and vertical alignments at curve 3 (near a sag vertical curve)

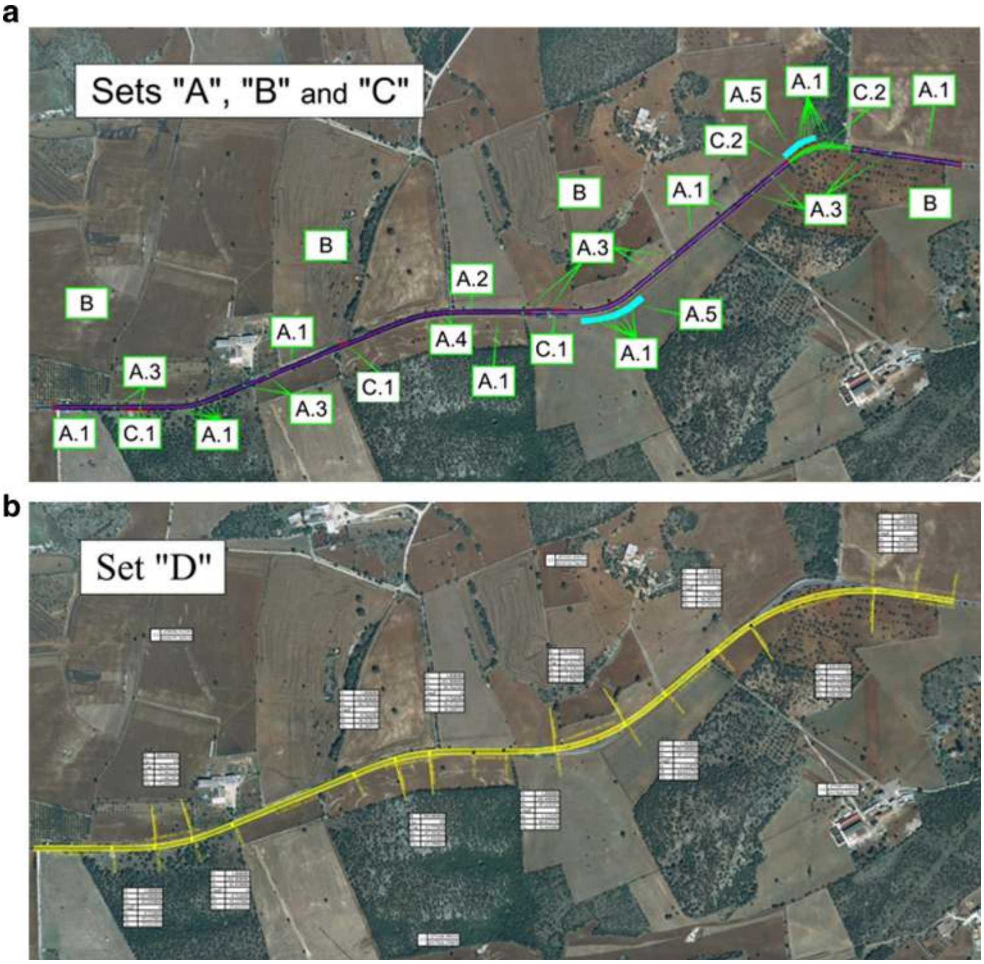


Fig. 11 Example of possible different sets of countermeasures. Site PP1: **a** short-term safety measures (sets of countermeasures "A", "B" and "C"), **b** redesign of the horizontal alignment (set of countermeasure "D")

unfeasible, then systems for reducing speed together with a better danger signalling near driveways should be implemented. In any case, the introduction of roundabouts in the place of minor intersections (especially 4-legs) could conduct to safety benefits. These possible solutions are graphically summarized in Fig. 12.

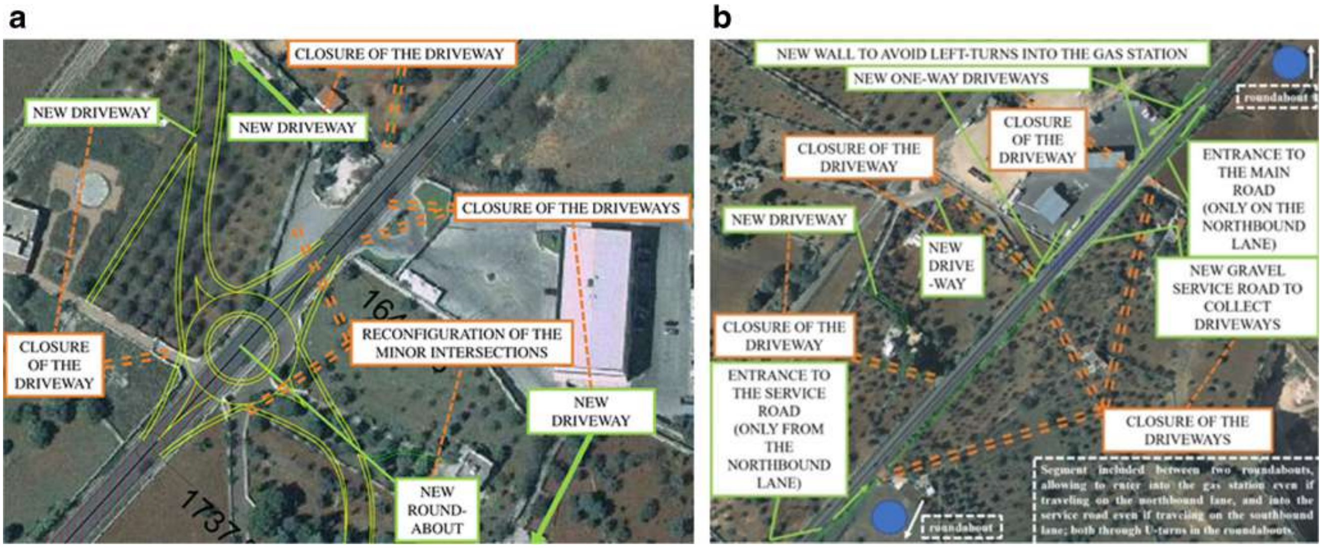


Fig. 12 Possible solutions of driveways/minor intersection-related issues. Site PP2: **a** example of roundabout for enhancing minor intersection geometry, **b** example of service roads and driveways recollection through minor roads

Problem/solution 3.3.C The comparison with actual standards and regulations could highlight that the road section is not adequate: a) geometrically, i.e. standards for widths or alignments are not respected; b) functionally, i.e. the cross section is not sufficient for the role played in the territory or the traffic volume. This was valid for both the sites PP1 and PP2, and it can be a very common condition (see 3.2.A). If the *adaptation to standards* is not expressly required by the project, it should be pondered by considering the expected safety benefits (e.g. increasing shoulder width of 0.2 m for adapting it to standards could be not necessarily related to a benefit commensurate to its cost).

Problem/solution 3.3.D Automated speed enforcement is considered in the CMFs related to the two-lane rural road HSM SPF. Anyway, no clear indications about the speed to be posted in combination with the enforcement are given. Apart from enforcement, when selecting countermeasures, *posted speeds* should be set according to safety checks regarding sight distance, speed differences [69], and road friction (in coherence with local regulations). This means that the maximum speed which simultaneously allows the verifications of all the cited safety checks can be considered as the "safe speed" to be posted [70]. Based on this principle, at site PP1, the speed limit of 60 km/h was proposed. This speed can satisfy the three safety checks regarding speed differences of subsequent elements, sight distance, friction. The Friction Diagram based on this posted speed is shown in Fig. 13.

Problem/solution 3.3.E As previously discussed, there could be several possible different safety measures for solving the same types of identified issues. Thus, the authors proposed to individuate "sets" of countermeasures rather than several different countermeasures, based on their aim and timely application. For example, at site PP1, almost all accidents were run-off-road crashes and problems concerning alignment, road consistency, speeding, skidding risk, drivers' perception were highlighted. Hence, different sets of countermeasures were selected considering different common aims and timely applications (see Table 3). Sets A, B, C are short-term measures, inexpensive and easy to be implemented. However, they differ due to the specific strategy used for solving the problems: A) acting on the driver's perception, B) acting on speeds, C) acting on the road friction and the consequences of run-off-road crashes. Each of these strategies (or a combination of them) can have a potential impact on safety, even if it could not completely address the problem. A more radical countermeasure, to be implemented in the long-term period and requiring significantly higher costs, is the reconfiguration of both the horizontal and vertical alignments, by complying with the road standards. However, this choice could also lead to significantly higher benefits (see Section 3.4).

3.4 Choice among different projects

Costs and benefits for each set of measures are computed (see 2.4), by using the calibrated HSM as reference predictive method. Other methods, suitable for the context and road types considered, were assessed in next section.

For the site PP1, the Net Present Value (NPV) (see Eq. 4), the Benefit-Cost Ratio (BCR) (see Eq. 5) and the Incremental Benefit-Cost Analysis (see 2.4), were used for conducting economic assessments. All the possible combinations of the different sets related to the short-term period were evaluated, besides of the long-term alternative. Different methods could lead to very different results (e.g. the BCR method can provide high ranks for inexpensive measures, but providing notably small benefits). Considering the incremental BCA analysis, the most effective combination, commensurate with its costs, is the sum of all the short-term measures A + B + C. The set D was not considered in the economic assessment because it was unfeasible due to the presence of environmental constraints with respect to modifications of the existing road (Table 4).

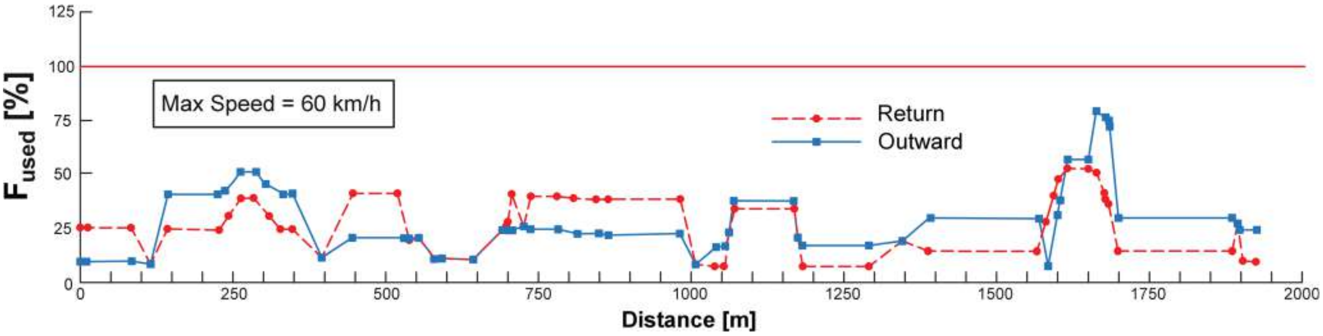


Fig. 13 Friction Diagram of Site PP1 in wet conditions, in case of compliance with the speed limit of 60 km/h

Table 3 Sets of countermeasures chosen for site PP1

Set A	Set B	Set C	Set D
1. Raised profile line markings on the curves 1, 3 and 4 2. Transverse rumble strips across the full lane in approaching at curves 3. Reflective raised pavement markers 4. Curve warnings and guidance systems 5. Insertion of QuercusTrojana on the outer side of the curves 3 and 4 for improving their perception	Installation of an automatic speed control system for the entire road segment	1. Replacement and upgrading of the roadside barrier with bridge crash barriers at different points 2. Replacement of the friction course with SplittMastix Asphalt at curve 4	Reconfiguration of the horizontal and vertical alignments of the entire road segment according to the Italian road standards for a "C2" category (secondary rural road)

The combination 7 can be able to reduce or eliminate most of the problems highlighted during the diagnosis stage. In particular, the automated speed control with speed posted to 60 km/h, can drastically reduce both the possible skidding risk (wet conditions) and the stopping distances. Therefore, it provides a higher safety level to the whole segment analyzed.

3.5 Selection of alternative predictive methods

Given the countermeasures considered for both the sites PP1 and PP2, a comparative assessment of the most suitable methods for taking into account the different sets of measures was conducted. In detail, besides the HSM-based prediction, the two local predictive methods reported in Section 2.5 (Eqs. 6 and 7), proposed by namely Cafiso et al. [28], and Russo et al. [30]; are considered. This has not to be intended as an assessment of the considered methods themselves, but rather as a simulation of the decision process between different predictive methods to be used by practitioners, in case of presence of locally available models.

Taking the countermeasures for site PP1 listed in Table 3 as a reference, the sets A, B and C could not be assessed through local predictive methods [28, 30] for the scenarios before and after interventions. In fact, markers, rumble strips, signs, trees, speed control, friction and road barriers are not variables of the local models. Actually, most of them, except for centerline rumble strips and speed control, are not considered by HSM models too. Hence, additional sources should be consulted for computing safety benefits (e.g. [50]). Conversely, the set D (Table 3), including alignment and road standard modifications, can be potentially assessed by all the methods considered, since they include geometric variables. However, synthetic geometric variables based on the overall alignment, may lead to estimates related to the whole section, rather than on the sum of short homogeneous segments, as in the HSM method.

Whereas, the countermeasures of site PP2 (see Fig. 12) (excluding those involving intersections not considered here), mostly aim at reducing driveways. Driveway density is included as a variable in the models by the HSM and by Cafiso et al. [28]. In this example, prediction

Table 4 Site PP1. Economic assessment of the different project alternatives[a]

Set	Combination	Costs[b] (€)	Benefits[b] (€)	NPV (€)	BCR	Inc. BCA
A	1	280028,20	3402961,87	3122933,67	**12,15**	4
B	2	136261,61	1665087,70	1528826,09	**12,22**	6
C	3	226063,26	461302,01	235238,75	2,04	7
A + B	4	416289,81	4829842,24	**4413552,43**	11,60	**2**
A + C	5	506091,46	3786056,35	3279964,90	7,48	3
B + C	6	362324,88	2094098,57	1731773,69	5,78	5
A + B + C	7	642353,07	5186120,11	**4543767,04**	8,07	**1**
D	8	8771813,23	59272141,96	/	/	/

[a] The two more convenient alternatives are highlighted in boldface for each method used

[b] Costs and benefits were actualized considering the whole life of the measures (10 years for short-term, 30 for long-term measures)

Table 5 Sources for models able to quantitatively estimate safety benefits of the different measures considered

	Pilot projects	PP1				PP2
	Set of countermeasures	Set A	Set B	Set C	Set D	–
Possible methods	HSM base [6]/calibrated [48]	x	x		x	x
	Cafiso et al. (2010) [28] (Eq. 6)				x	x
	Russo et al. (2016) [30] (Eq. 7)				x	
	Other sources needed (e.g. for CMFs: [35, 50])	x		x		

models not including driveways, could not be useful for estimating benefits.

A summary of the suitable methods among the predictive methods considered, for each set of countermeasures proposed for the site PP1 and for the countermeasures of site PP2, is shown in Table 5.

Since for the site PP1 (set D), the $\Delta N_{expected}$ can be estimated by using all the three presented predictive methods, the comparison of the three different outcomes is computed and it is reported in Fig. 14.

It can be immediately noted that predictive methods may provide significantly different $N_{expected}$ (before/after) and $\Delta N_{expected}$ estimates. Moreover, local models provide significantly lower $N_{expected}$ (before/after) than those based on the HSM method (both calibrated and uncalibrated), as stated in literature for the Italian two-lane rural road segment case (see e.g. [30]). The over-dispersion parameter k associated to the specific predictive model influences as well the estimates, since the weight factor assigned to the predicted frequency in the EB method is based on this parameter (see e.g. the $N_{expected}$ values based on Russo et al. [30] for different k parameters used). However, the attention should be mainly focused on the $\Delta N_{expected}$, rather than before/after estimates, since the safety benefit assessment is mainly based on it. The $\Delta N_{expected}$ based on [30] is very low, because among all the variables included in the model, the only one affected in the "after" scenario is the lane width. Whereas, the other $\Delta N_{expected}$ estimates are significantly higher and comparable between them. In fact, in the predictions based on the HSM and on Cafiso et al. [28], more geometry-related variables are considered, then explaining the high crash reductions when modifying aligment and geometric standards. Clearly, no general conclusions about transferability and model assessments can be made, due to the limited application conducted. However, as expected, the model choice should be influenced by the types of countermeasures and the variables considered by the different models, in order to obtain reliable results. In this sense, a calibrated HSM model has the advantage of being potentially suitable for considering several countermeasures types, even if the associated CMFs were developed in a different context. However, the crash reduction outcome, in this limited example, is comparable with results from the local SPF by Cafiso et al. [28], able to consider different aligment and geometric changes.

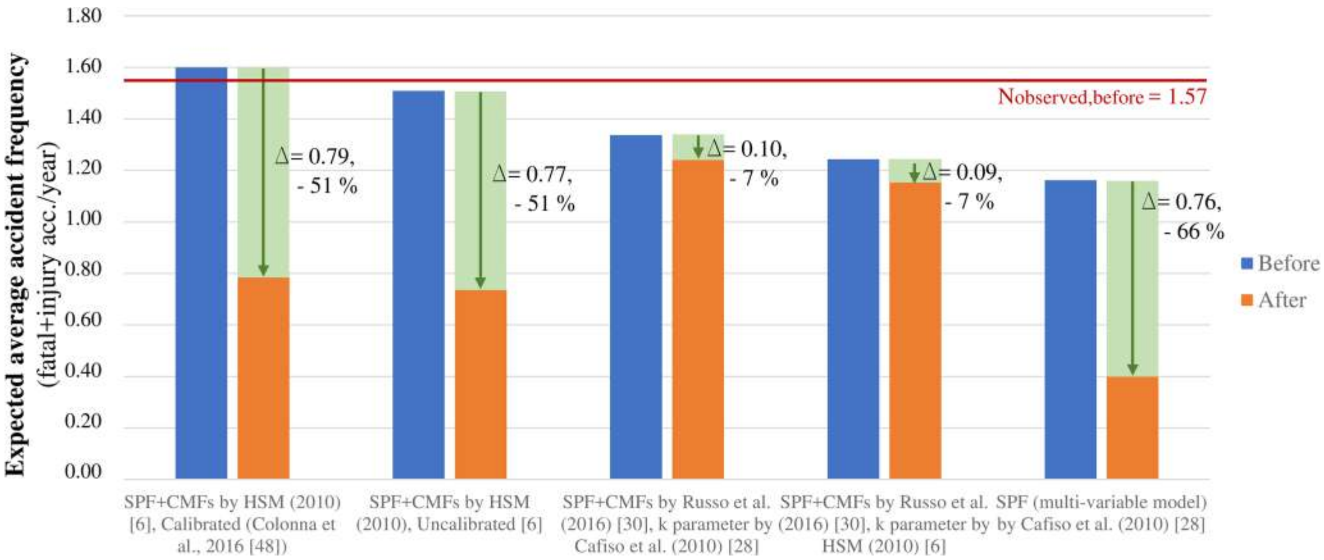


Fig. 14 Expected average accident frequencies on the PP1 site before and after the intervention (set of countermeasure D), by using three different predictive methods

4 Conclusions

A possible operational protocol to design safety interventions on existing two-lane rural road segments based on the calibrated HSM method, the EU Regulations, local standards and research contributions was presented. Its application to real design projects was shown through examples. Several possible recurring problems and solutions were discussed, by using the applications as a reference. Based on these, conclusions about main advantages and disadvantages of the method used are drawn as follows.

Main advantages of the proposed method are: the rigorous methodology for individuating both safety problems on the existing roads and possible interventions, the comparative quantification of the safety benefits and the applicability of the general method independently from the particular State or region (but considering local regulations and standards). The proposed method could be immediately applied in regions/areas where a HSM calibration study or suitable local SPFs are available. The estimate of the friction used along the road, depending on a wide list of factors, is another advantage of this integrated method, to be potentially used during both the diagnosis and design stages.

The main disadvantage is instead the necessity of local data, in particular both a valid calibration factor for the baseline HSM model (or suitable locally-derived Safety Performance Functions) and recent data of observed accidents and traffic volumes. Anyway, the research in the field of safety, together with the increasing attention paid by local authorities, could help in an immediate future in filling the eventual gaps related to those matters. Moreover, results of real data assessment and evaluation of real implementation on existing roads should be needed in future studies, in order to check the reliability of the proposed protocol.

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