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Article

A Straightforward Framework for Road Network Screening to Lombardy Region (Italy)

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Abstract: It is not possible to deal with sustainable mobility without considering road safety as a key element: Target 3.6 of the Sustainable Development Goals aims at halving the number of road deaths by 2030. To do so, further effort and effective tools are required for road authorities, to implement improvement measures and enhance road safety for all. Road network screening (RNS) is the first step of the whole Road Infrastructure Safety Management (RISM) System process. It is applied to a wide scale to assess the safety performance of the whole road network and identify the worst performing roads (or sites). The literature is quite rich with RNS models and methods, which have greatly improved, recently. Moreover, although many national frameworks on road safety have been issued over time, some barriers remain, specifically related to data quality, such as accurate crash location, which is mainly used to integrate crash data with other databases. In addition, most of these frameworks adopted partial indexes to identify black spots and presented results using fixed maps for visualization. This paper fills these gaps by the proposal of a straightforward operational framework to perform RNS, based on a simple and flexible rationale to integrate raw crash, traffic, and road data. Specifically, the framework: (i) manages crash location data, without relying on plane or geographical coordinates, which are missing or inaccurate and still are a crucial issue in many European countries such as Italy; (ii) adopts an adjusted accident cost rate index that integrates frequency and severity of crashes as well as a measurement of exposure; (iii) introduces variable maps that show the results at different jurisdiction levels. A relevant case study demonstrates the usefulness of this framework using 30 000+ crash data of the whole non-urban road network of the Lombardy Region (Northern Italy). Road authorities could adopt this framework to perform an accurate safety screening on the overall regional road network. Moreover, this framework could be implemented in a road traffic safety managerial system to better prioritise safety interventions within a tight budget and help achieve sustainable development targets.

Keywords: road sustainability; road network screening; Road Infrastructure Safety Management System; crash location; data integration; operational framework

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1. Introduction

Sustainable mobility plays a crucial role in the worldwide vision towards sustainable development. However, it is not possible to talk about sustainable mobility without accounting for road safety as an essential component. Indeed, Target 3.6 of the Sustainable Development Goals set by the United Nations, aims at halving the number of road deaths by 2030. Accordingly, worldwide, road safety strategies have been set to halve the number of road deaths and serious injuries by the next decades, e.g., [1]. Although great improvements have been achieved worldwide (and especially in Europe) over the last decade, road unsafety still represents a huge health, social, and economic burden that causes approximately 1.3 million deaths each year and is recognized to be the leading cause of death for people aged 5–29 [2]. In addition, the road crash (or accident) costs range from 0.4% to 4% of the national Gross Domestic Product (GDP) across countries [3]. Conversely, in a sustainable perspective, such resources should be employed more effectively, by providing road safety experts and practitioners with tools and strategies to tackle such a silent and long-lasting pandemic. As a result, further effort is required to be prepared for the next decade of action.

Specifically, from an engineering and technical perspective, the Road Infrastructure Safety Management System (RISMS) provides a set of managerial tools (or procedures) to assess the road safety performance over the entire life cycle of road infrastructures [4,5]. More precisely, each tool is conceived for a specific stage (e.g., project, operation), aim (e.g., monitoring, auditing), and level (e.g., network-wide, site-specific). According to the European Union , the RISMS procedures must be implemented on all roads belonging to the TEN-T network [4,6]; however, Member States are warmly recommended to implement them also on other roads, which are classified as primary in the national network [6,7]. As for existing roads, RISMS procedure starts with the safety evaluation of the whole road network to identify the most critical elements (i.e., segments and/or sites) and then proceeds with in-depth analysis to assess specific problems and set effective countermeasures [8–10].

Road network screening (RNS) is the first step in the whole RISMS procedure, and it is applied to a wide scale. Its scope is the identification of hazardous road elements that have abnormally high number of crashes, a high share of severe crashes, or a high share of a particular type of crash: these elements deserve priority of action for a successful road safety management process. RNS can be performed over the entire road network within a jurisdiction or be limited to a specific road class, e.g., [8]. Usually, RNS involves road segmentation (e.g., road sections, sliding windows), black spots (hotspots, hazardous locations, or high road crash sites), identification, and visualization, respectively.

RNS is not a novelty in the transportation community: the literature on this topic is quite rich, and several are the models and methods applied in RNS, which are performed by different approaches, e.g., [10–12].

On the one hand, RNS models rely on sophisticated and elegant statistical prediction functions that relate attributes (e.g., road design and functional features) to the response variable (e.g., crash frequency, etc.) using historical data [13,14]. Some examples include Binomial and Beta-Binomial models [9], Empirical Bayesian Methods, Excess Empirical Bayesian Methods, Bayesian Poisson Log-Normal models [11,15,16], or mixed-multivariate models [10]. Nevertheless, knowledge and expertise are required to develop, perform, and interpret such models, and specific software or coding skills might be required too. For instance, according to [17], there are some critical points of the modelling approach, such as the fundamental assumption of probability distribution for crashes counts and the functional specification of the several variables. Failures in these issues could lead to misleading results. In addition, this approach is data intensive and needs relevant effort to collect and process data as well as calibrate the resulting models [18,19].

On the other hand, many European Countries delivered specific RNS methods—or frameworks—for example, [20–22]. As opposed to existing models, these frameworks rely on the computation of simple or composite indices (e.g., accident frequency, accident rate) to identify the worst performing road network elements. Moreover, its simple properties make this approach the most adopted from many experts of road safety—e.g., [20–24]. However, technical issues such as data availability and processing and integration among data sources have not been fully addressed, especially in the case of mis-recorded and mis-reported data: these are fundamental issues for any applicability and replicability of these methods, e.g., [25]. Moreover, almost all of these studies proposed indexes that do not include a simultaneous computation of the accident risk (i.e., frequency and severity of crash, exposure term) and do not report variable maps showing the safety performance for administrative levels. Conversely, using the accident risk concept by a complete index that emphasises where attention is required could provide a complete overview of the safety performance onto the road network, hence it could be preferred for safety analyses. Moreover, providing variable maps at different administrative levels could emphasise where priority of intervention is required at regional, provincial, and local levels, respectively.

The proposed study aims at bridging the gaps related to RNS methods in European countries by proposing a straightforward operational framework to perform RNS at different administrative levels. Specifically, this framework is based on a flexible network segmentation rationale and, by integrating three data sources, i.e., base-map, traffic, and crash data, it is organised in five steps: 1) network segmentation through the definition of the paths; 2) assignment of road and traffic attributes and 3) crash attributes to each path; 4) computation of the safety index for each path; 5) ranking the safety of each path and showing results by easy-to-read dashboards built in Geographic Information System (GIS) environment.

Focusing on the European context—which is considered among the safest in the World in terms of road safety [26]—this framework expands the current operational frameworks spread in many EU Countries. Unlike existing frameworks, it: (i) handles crash data in a 'wide' scale, without using, e.g., plane and/or geographical coordinates because these coordinates are still missing or bad recorded in many countries; (ii) uses other location attributes to associate the crash and related traffic and base map attributes to a road segment; (iii) adopts an adjusted accident cost rate index (AACRI) that aggregates in one measure the main components of risk, i.e., the frequency of accidents, the exposure measure, and the severity (evaluated by the social costs); and (iv) uses variable maps that show the values of the AACRI at different administrative levels: the road may exhibit safer conditions at the regional than local level; thus, only the local administration can act at improving its safety performance in its jurisdiction.

A total of 30,000+ crash data occurred between 2014 and 2018 from the whole non-urban road network of the Lombardy Region (Northern Italy) were adopted to demonstrate the viability of this framework in a real case study. Variable crash risk maps are adopted to show the results.

This study attempts to contribute to both theory and practice. On the theoretical side, it provides a novel and flexible rationale to link data from different data sources, which is a crucial step to perform comprehensive and effective road safety analysis. More precisely, this study processes crash data not locally, but diluting them in the scale of longer road sections and uses other location attributes such as road name (or code) and jurisdiction name (or code) to analyse all crashes data without losing anyone. This novel approach addresses potential problems related to missing or inaccurate coordinates of crashes that still are crucial issues in many countries. From a practical perspective, this study provides Road Authorities and Administrations—which are responsible for road safety and sustainable mobility at the different levels—with a solid, adaptable, flexible, and effective decision support tool. It helps them in evaluating the overall safety performance of the road network, defining actions priority, and directing further required analysis in a more cost-effective manner.

The remaining paper is organized as follows. Section 2 provides a concise state of the art on RNS methods. Section 3 presents a straightforward framework to estimate the adjusted accident cost rate index. Section 4 introduces the real application of this framework in Lombardy Region. Section 5 presents the results and discusses them. Finally, Section 6 concludes the study and provides research perspectives.

2. State of the Art on Road Network Screening Methods

Many studies have addressed safety screening by adopting RNS methods, especially in the context of European countries. A concise summary of these studies is shown in Table 1, which is described in what follows by pinpointing possible pros and cons for each study.

Table 1. A summary of studies on RNS methods. Table 1 is a representative (not exhaustive) list of reference of RNS methods.

Authors	Country	I - Road Segmentation	II - Black Spot Identification	III Black Spot Visualisation	Pros	Cons
Austrian Guideline Code, [27]	Austria	Fixed length Sliding windows	Accident rate	Tables, fixed maps	• Exposure measurement considered	• Necessary accurate accident locations (plane or geographic coordinates) • Necessary traffic data • Severity is considered a part
Vistisen, [28]	Denmark	Sliding windows for road section, variable length	Test on the Poisson distribution model	Tables, fixed maps	• Necessary only data accidents	• Necessary accurate accident locations (plane or geographic coordinates) • Severity and exposure measurement are neglected
SETRA, [20] [1]	France	Road, Road portion, road section, sliding windows, fixed	Safety Potential	Tables, fixed maps	• Economic impact of missed accidents • Measurement combined for the segment and the sliding windows	• Necessary accurate accident locations (plane or geographic coordinates) • Frequency, severity and exposure information clustered in two indexes • Necessary several source of data • Proprietary software
German Road and Transportation Research Association, [29]	Germany	Accident maps inspected	Accident frequency	Maps	• Straightforward index • Necessary only data accidents	• Only graphical representation • Necessary accurate accident locations (plane or geographic coordinates) • Severity is included by mean of critical values • Exposure is neglected

Elvik, [21][2]	Belgium (Flanders), Hungary, Norway	Fixed length Sliding windows	Accident frequency	Tables, fixed maps	• Straightforward index • Necessary only data accidents	• Necessary accurate accident locations (plane or geographic coordinates) • Severity and exposure measurement are almost neglected (e.g., severity by mean of weights)
Elvik, [21][2]	Switzerland	Fixed sections of variable length	Accident frequency	Tables, fixed maps	• Straightforward index • Necessary only data accidents	• Necessary accurate accident locations (plane or geographic coordinates) • Severity is included by mean of critical values • Exposure is neglected
Elvik, [21][2]	Portugal	Fixed length Sliding windows	Accident rate	Tables, fixed maps	• Exposure measurement considered	• Necessary accurate accident locations (plane or geographic coordinates) • Necessary traffic data • Severity is considered a part, depending on the definition of black spot considered
Euro RAP, [22]	Europe	Roads	Accident rate	Tables, fixed maps	• Exposure measurement considered	• Necessary traffic data • Aggregate index for the overall road • Severity is considered a part • Gradual Fixed value ranking scale • Proprietary software

MIT, [23]	Italy	Fixed length and cross-section segment	Accident rate, Accident frequency, Number of Accidents	Tables	• Straightforward index • Exposure measurement considered • Index flexibility based on data availability	• Necessary traffic data • Necessary Segment cross-section feature • Severity is considered partially
Mamčic and Sivilevičius, [30]	Lithuania	Road portion	Accident rate	Tables, fixed maps	• Exposure measurement considered	• Necessary accurate accident locations (plane or geographic coordinates) • Necessary traffic data • Severity is considered a part
FHA, [31]	USA	Fixed length Sliding windows	Set of performance measures	Tables	• Performance measure flexibility based on data availability	• Necessary accurate accident locations (plane or geographic coordinates) • Roadway information for road categorisations always needed • Exposure measurement not always considered
This paper	Italy	Road section of variable length also depending on the administrative boundaries	Adjusted accident cost rate index	Tables, variable maps include several administrative boundaries	• Unnecessary accurate accident locations • Frequency, severity, and exposure measurement clustered in one index • Economic impact of occurred accidents	• Necessary several data sources

1. Updates have been issued in 2012 and 2021. However, they are not available online. 2. Elvik [21] is indicated as reference as no specific national Guideline or Manual was available online or they were published in the national languages which authors do not know.

As it has been concisely argued before, RNS usually involves three fundamental steps: (I) road segmentation; (II) black spot identification; and (III) black spot visualisation. Each step is briefly summarised in what follows.

Road segmentation (I) aims at dividing the entire road network considered into more manageable elements for the evaluation of the road safety performances. Road segmentation can be performed in different manners, e.g., [11,32], which can be grouped into two main categories:

- Distance/geometry-related segmentation, where the process splits the entire road network into defined segments, whose endpoints correspond to given road characteristics or fixed distance. (e.g., fixed length sliding windows, homogeneous segments), e.g., [33,34].
- Crash-related segmentation, where the process splits the entire road network based on road crash attributes to identify the endpoints of the road unit (e.g., High Crash Risk Profile), which usually requires sophisticated models [35].

The former category is the most used. The road elements can be defined according to several scales of representation: (i) 'macroscopic' scales include overall roads, road portions, and road sections, or (ii) 'microscopic' scales usually considers sliding windows, i.e., fixed length road sections (e.g., 100 m in Norway, 250 m in Austria, etc.) that slide along the road course to identify black spots. For instance, according to [20], a road is defined as a link between two major hubs or important junctions; a road portion is a piece of road whose length is compatible with the study capabilities of the service; a road section is a segment defined by considering a homogeneity of the cross-section, the traffic, and the environment. In addition, the segmentation can be usually drawn by homogeneous Annual Average Daily Traffic (AADT), roadside hazard and curves, and clusters, e.g., [11,20]. Most of European safety guidelines consider a network segmentation based on fixed length sliding windows (e.g., Austria, Belgium, Hungary, Norway, and Portugal). Additionally, at the international level, the Highway Safety Manual (HSM) adopts the fixed length sliding window in its process [31].

Once a proper segmentation has been considered, the black spots identification (II) follows. This identification is a systematic process of isolating road elements (e.g., road sections, sliding windows) that have an unacceptable 'quota' of crashes, on the previous segmentation, e.g., [20,21]. How much is the unacceptable 'quota' of crashes is searched according to an index-based approach. This approach relies on the computation of simple or composite safety indices for each road element to derive the worst performing conditions along the road network at hand. Since there are many indices that can be used for this purpose, we focused on the most adopted. Some studies considered the crash frequency, i.e., the absolute number of crashes or per length unit. Once it is computed for each element, it is compared against a threshold based on a minimum number of crashes to check if the element can be identified as a high road crash site. For instance, in Hungary, a black spot is defined as a location where at least four accidents have been recorded in the last three years on a road section longer less than 1 km. Some countries, e.g., Belgium, expanded this index by also including some severity measures.

Some other studies adjusted the accident frequency and computed an accident rate by including an exposure measure too, e.g., [11,16,21]. This index is adopted in Austria and Portugal as well as in Lithuanian. In addition, it is adopted by EuroRAP [22] where the ratio between the number of crashes and the billions of vehicles*km travelled for the overall road is computed. This ratio is compared against a gradual scale with fixed thresholds to identify black spots needing priority.

In France, a safety potential index is computed by the ratio between the costs of avoidable crash and the kilometres of the considered road, as follows. First, the crash rate for each road section and the crash frequency for each sliding window are computed to label each of them with these indexes, respectively. Next, they are compared with reference values to identify the high road crash sites—i.e., the critical road sections or the so-called *Sections d'étude à Risque Anormal* (SRA)—(by a fixed rate for road types) and the critical sliding window or the so-called *Zones d'Accumulation d'Accidents Corporels*—ZAAC—(by a minimum of five accidents), respectively. Next, for each SRA and ZAAC, the computation of the number of evitable crashes is performed as a difference between those observed and those of reference in a fixed time horizon. Finally, this difference is multiplied per the average cost of a dead, a severe, or light injury per the respective quota of observed crashes to obtain the overall costs. Then, this value is divided by the length of the considered road.

Finally, in Germany, hot spots were identified by using maps showing plots of accidents. A total of five accidents occurred in a year (all types) at a location up to 100 m or in three years (only at least with injuries) at any location is the threshold over then a black spot is identified [29].

At the non-European level, the HSM provides a set of *performance measures* to be used in evaluating the potential to reduce the number of crashes or crash severity at a site. The list ranges from more simple indicators (e.g., simple average crash frequency, crash rate, relative severity index, etc.) to more complex and sophisticated methods (e.g., Expected average crash frequency with Empirical Bayesian adjustments). However, the selection of one measure or another depends on data availability about facility information, crash data, traffic volume data, and, in some cases, safety performance functions [31]. Besides the average crash frequency and the crash rate, the HSM introduces other indices, such as the Relative Severity Index (RSI). More precisely, monetary crash costs are assigned to each crash type and the total cost is calculated for each site. Then, such value is compared to an overall average crash for the reference population. The sites experiencing higher crash costs than the average ones are those where interventions are required.

At the end of black spots identification, their visualisation (III) follows. Indeed, a key factor for the effective analysis of crashes data is to build comprehensible and usable performance reports, which are easily understandable for planners, senior managers, and decision makers to prioritize interventions. The visualisation may be obtained by using tables, maps, or both. For instance, [20] reported tables where the list of overall roads needing intervention is ranked according to the safety potential index and some maps showing the crash rate for each segment where the SRA and ZAAC were highlighted. EuroRAP [22] returns the risk maps to indicate the actual fatalities and injuries number on a road network and the reported data for the overall road.

Undoubtedly, all these studies have contributed to the RNS and provided valuable results. However, some gaps persist.

To begin with, as for road segmentation, fixed length sliding windows or simple fixed length segments could generate inaccuracies in the detection and extension of critical road sites [21]. Moreover, this approach requires accurate crash location (i.e., plane or geographic coordinates) to associate crash to the proper position (and, therefore, road segmentation unit), especially in applying the sliding windows method. This is particularly relevant because, although almost all the studies used accurate crash location as an input (which is supposed to be available for each crash), in Italy, it would be challenging to rely on, e.g., sliding windows because 36% of rural road crashes do not completely report the location information [32]. As a result, if many road crashes cannot be associated to the related road network element due to the lack of detailed location attributes, they can be excluded from the analysis and, therefore, the measure of the road safety performance could be biased, e.g., [36,37]. Conversely, relying on a segmentation that does not use plane and/or geographical coordinates could also provide an accurate screening of the network, because all crashes data are considered. In addition, if segmentation based on road homogeneous characteristics is applied, it requires a detailed amount of data, which are not always available. Indeed, data quality and availability issues are some of the most challenging problems in road safety analysis. Data quality is subject to the aim of the specific use; therefore, datasets which are created for other purposes might not be suitable for other employments, e.g., [32,36]. Similarly, it is well known that crash data are subjected to many uncertainties and inaccuracies, and location attributes are among the most affected information, e.g., [25]. As for data availability, problems arise when key variables (and related data) are missing or are mis-recorded, although they may be extremely useful to integrate crash data with other databases, as crash location attributes do [22,25,36,37].

Second, as for black spot identification, all exiting studies adopted straightforward indexes that usually did not aggregate the main components of risk according to the classical index first introduced by Fine [38]. He considered the potential crash consequence (a driver is the severity), the exposure factor, and the probability factor (a driver is the frequency). As it has been shown in Table 1, most of all studies considered only the crash frequency, several included measurements of exposure also. SETRA [20] considered frequency, severity, and exposure information, but these components were clustered in two indexes before computing the safety potential. EuroRAP [22] is an easy procedure to replicate. However, the data input process is manual, thus roads should be already pre-identified, and the related number of road crashes already associated. Moreover, although an adjustment factor is provided, since the classification scale is fixed and more oriented to compare countries, it might not be fully representative of the specific network analysed.

HSM [31] provides an RSI index that considers crash severity through the related monetary costs, but it does not consider exposure measure. In addition, barriers to the implementation of RNS also concern operational factors, such as the availability and need of using proprietary software and tools to perform the analysis. However, such tools and procedure may be subjected to some restrictions (i.e., subscription licences) and might not be provided with technical guidelines, which are essential to replicate the work [5,8,18].

Third, as for black spot visualisation, although GIS have been extensively used for many years by Departments of Transportation and Highway administrators, no study reported variable maps that can exhibit different safety conditions at several administrative levels. This is a relevant issue because the overall road may exhibit safer conditions at the regional than local level; thus, only the interested local administration can work to improve the safety performance on its context.

Finally, data pre-processing is still a recurrent drawback, as it strictly influences road safety analysis outcomes. Many studies usually describe the data used in the research but no exhaustive indication on their integration, processing, and managing is provided, and a replica of the studies is at least tricky.

As highlighted in the last row of Table 1, this paper aims to cover the former gaps.

3. Methodology

In this section, the operational framework for RNS is presented. Building on [22], this framework is organised in five steps and provides a feasible and flexible structure to integrate raw crash, traffic, and road data to return an accurate spatial resolution. The overall framework is conceived according to two main assumptions: first, road network safety assessment should include road crashes frequency, severity, and exposure measures (e.g., length of road segments and traffic volumes). Therefore, crash, road, and traffic data should be linked to perform such assessment. Second, to integrate all the data sources involved, a spatial resolution, which does not rely on plane or geographical coordinates of crashes, should be defined. Figure 1 represents the scheme of the operational framework, and each step is briefly described in what follows.

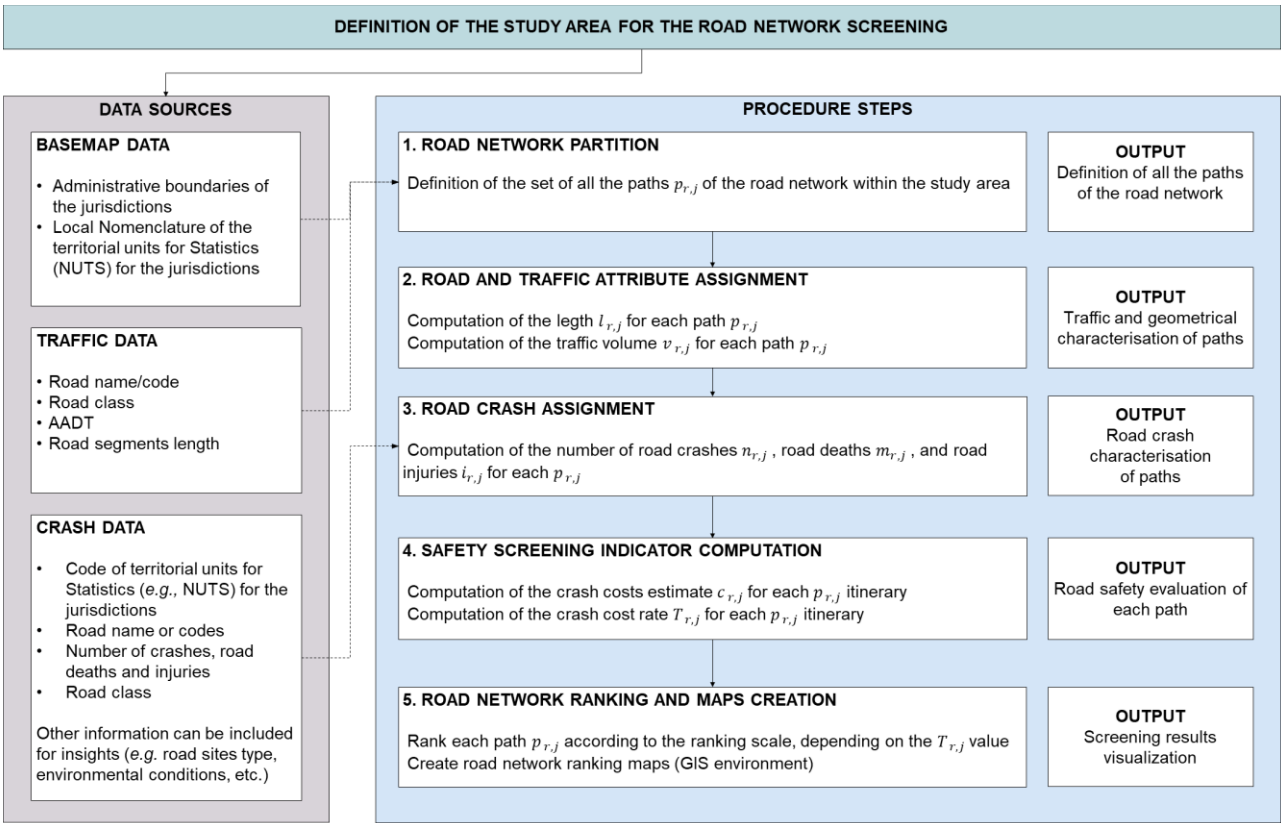

Figure 1. Operational framework scheme (authors' elaboration).

At the beginning, the study area must be defined for the road network screening, to select the related information required for the different data sources and, therefore, to perform the several steps of the procedure.

3.1. Data Sources

The "Data sources" box contains the main sources from which the mandatory information should be gathered. Specifically, these are:

- **basemap data**, i.e., the main map and GIS-based data, which refer to the administrative partition of the selected territory. Specifically, the data about the territorial units for statistics (i.e., *NUTS*) and related boundaries elements are required. Such data are generally provided as a GIS-based file but also the related spreadsheets are available.
- **traffic data**, i.e., road identification and traffic volumes data, which refer to mobility patterns. They are considered in terms of link-node basis, where the node represents either an intersection or a change in the cross-section design and the link in the segment of path. More precisely, road name or code are necessary to identify the route. As for traffic volumes, data can be collected by the mean of site measurements or traffic modelling. Such data are generally provided as a GIS-based file, but also the related spreadsheets are available. Additionally, the road class should be gathered, as it would be required to differentiate the screening for different road classes.
- **crash data**, i.e., road crashes occurred within the study area, the number of road deaths and injuries (i.e., severity attributes). In addition, crash location is required to match crashes to road paths (e.g., jurisdiction, road name or code). Other data (e.g., road site type, environmental conditions) may be useful for specific insights. Such data are generally provided as a spreadsheets file and are retrieved from national statistics template or police crash records.

Data can be provided in different formats and some data preparation could be necessary to refine data and make them consistent for the following steps (e.g., missing data completion, mis-recorded data correction).

3.2. Procedure Steps

Step 1—Road network partition and path definition

Road safety data are usually expressed through specific spatial units, which better fit to the nature of the related information. For instance, crashes are expressed as points on the road network, as they represent the single event with specific characteristics, whereas roads (and the related attributes) are expressed as sequences of segments (and intersections) with specific designs and traffic attributes. Note that in this study, a segment is defined as the portion of a road between two endpoints, which can be either road intersections or points where functional and geometric changes in the road section are observed. However, when it comes to match such information to perform road safety analysis (road crashes must be referred to the related road elements for such purpose), road crash metadata could lack information about plane or geographical coordinates. As a result, if many crashes cannot be associated to the related road network element, they may be excluded from the analysis and, therefore, return a misleading outcome in terms of road safety performances. Hence, it emerged the need to define an alternative road network unit that enables the connection of the several information and a univocal correspondence between road crashes and road elements. Such alternative spatial reference should be found by making the most out of the few—but always available—localisation information in the crash database metadata.

Such alternative road network unit should work as a "*least common multiple*" of the location attributes of all data sources available, on which the road network can be partitioned. To do so, first, all location attributes need to be identified among the different data sources. Then, only the common attributes of different data sources (i.e., basemap data, traffic data, and crash data) should be considered. Unlike road chainage and plane or geographical coordinates, the territorial jurisdiction (i.e., geographical and/or administrative boundaries) and the road name or code (which identifies a specific route) are usually reported in these sources. Usually, the same information is already registered in the road traffic data source but, if not, such information can be easily integrated by overlapping the road network with the lowest level of the territorial jurisdiction available (i.e., country, region, province, metropolitan areas, municipality, etc.) to perform a road network partition with as much detail as possible. Therefore, the "*least common multiple*" among location attributes is represented by the portion of a generic road within the boundaries of the lowest territorial jurisdiction. Such an entity is defined as a **path,** in this study.

For sake of clarity, Figure 2 provides a scheme to explain this concept. Within the study area (i.e., orange polygon), all the jurisdiction boundaries are identified (e.g., black polygons named j1, j2), as well as the road network to be considered (i.e., all the grey lines r1, r2, and r3). Each road is usually composed of a sequence of segments (i.e., the dashed green lines here reported with an offset from the grey line, for sake of clarity), which are delimited by the related nodes (i.e., the green points). Hence, the **path** of the road r1 within the boundaries j1 consists of the sequence of the segments of r1 within j1, i.e., s1,1,1, s2,1,1, and s3,1,1 (as reported in the zoom of Figure 2).

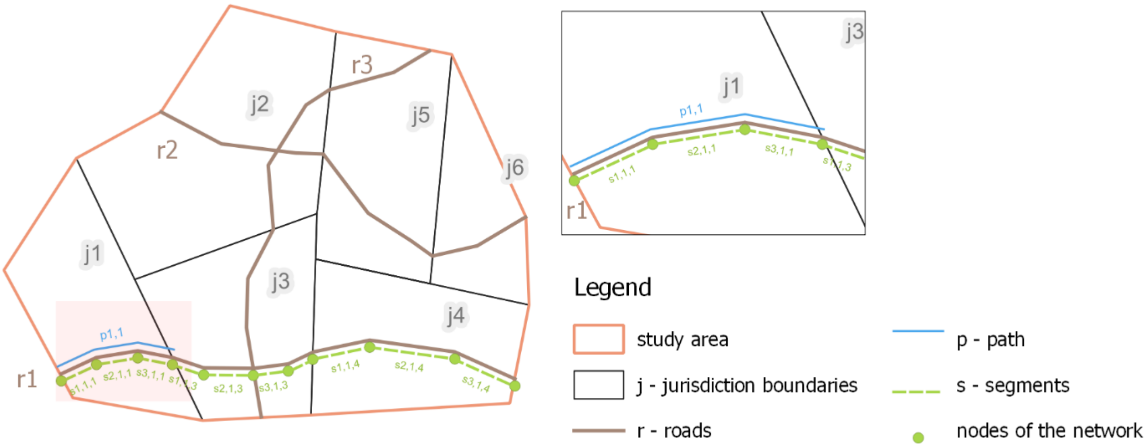

Figure 2. Conceptual scheme of the network partition and path definition.

According to such a definition, a path is not a fixed unit (such as the fixed length sliding window) but a variable (flexible) spatial road unit that depends on how the road network is and the level of the jurisdiction partition considered. Likewise, the jurisdiction partition considered depends on the level of detail of the spatial information available. Specifically, the more detailed the information available for all the data sources, the thicker the jurisdiction partition that can be considered, the more crammed the paths definition that can be reached over the entire road network and, overall, the more detailed road safety analysis can be returned.

As described previously, the segmentation process shows quite good adaptability and replicability to other contexts. To make it more general and provide a theoretical formulation of it to enable wide application, let:

- J be the set of the territorial jurisdiction within the study area, and $j \in J$ be a generic jurisdiction;
- $R(j)$ be the set of routes traversing jurisdiction $j \in J$, and $r \in R\ (j)$ be a generic road;
- $S(r,j)$ be the set of road segments of route $r \in R(j)$, $j \in J$, and $s \in S(r,j)$ be a generic segment;
- $P_{r,j}$ be the set of all segments $s \in S(r,j)$ of route $r \in R(j)$, $j \in J$, and $p_{r,j} \in P_{r,j}$ be a generic path.

Then, $p_{r,j}$ is defined as shown in Equation (1):

$$p_{r,j} = \{s \in S(r,j) \colon r \in R(j) \text{ and } j \in J\} \tag{1}$$

Step 2—Road and traffic attributes assignment

The second step assigns each path the related length and traffic attributes. According to the road and traffic data source, the road network attributes are reported on a node-link basis, so that each segment is associated with its length and the related Average Annual Daily Traffic (AADT) value. Moreover, the length and the AADT of $p_{r,j} \in Pr,j$ can be computed as the sum of the length and the AADT of each path's segment, respectively. More formally, let:

- l_s be the length of a generic segment $s \in S(r,j)$;
- v_s be the AADT of a generic segment $s \in S(r,j)$.

Then, the length (denoted by $l_{r,j}$) of path $p_{r,j} \in P_{r,j}$ of $r \in R(j)$ within, $j \in J$ is defined as shown in Equation (2):

$$l_{r,j} = \sum\nolimits_{s \in S(r,j)} l_s \qquad \forall\, r \in R,\ \forall\, j \in J \quad [km] \tag{2}$$

The AADT (denoted by $v_{r,j}$) of path $p_{r,j} \in Pr,j$ of r $\in R(j)$ within, $j \in J$ is computed as shown in Equation (3):

$$v_{r,j} = \frac{\sum_{s \in S(r,j)} l_s \cdot v_s}{l_{r,j}} \qquad \forall\, r \in R, \forall\, j \in J \quad [veh/day] \tag{3}$$

Specifically, $v_{r,j}$ is computed as a weighted average of the single v_s with respect to $l_{r,j}$.

Step 3—Road crash assignment

The third step assigns each path the related number of crashes, road deaths, and injuries. The crash data source contains all the crashes that have occurred over the road network of the study area considered. Each crash represents a punctual element on the network, with specific information about the crash characteristics. Specifically, the road and the jurisdiction where the crash occurred are registered for each element. Hence, the number of crashes, road deaths, and injuries of $p_{r,j} \in P_{r,j}$ of $r \in R(j)$ within $j \in J$ can be defined as the sum of the crashes, road deaths, and injuries having the same road and the jurisdiction attributes, respectively. More formally, let:

- $N\,(r,j)$ be the set of road crashes occurred on the route $r \in R(j)$, $j \in J$, and $n_{r,j} \in N_{r,j}$ be a generic crash;
- $M\,(r,j)$ be the set of road deaths occurred on the route $r \in R(j)$, $j \in J$, and $m_{r,j} \in M_{r,j}$ be a generic road death;
- $I\,(r,j)$ be the set of road injuries occurred on the route $r \in R(j)$, $j \in J$, and $i_{r,j} \in I_{r,j}$ be a generic injury.

Then, the number of crashes of path $p_{r,j} \in P_{r,j}$ of $r \in R(j)$ within, $j \in J$ is defined as shown in Equation (4):

$$n_{r,j} = \{n \in N(r,j) : r \in R\,(j) \text{ and } j \in J\} \quad [\#\, crash] \tag{4}$$

The number of road deaths of path $p_{r,j} \in M_{r,j}$of r $\in R(j)$ within, $j \in J$ is defined as shown in Equation (5):

$$m_{r,j} = \{m \in M(r,j) : r \in R\,(j) \text{ and } j \in J\} \quad [\#\, road\ death] \tag{5}$$

The number of injuries of path $p_{r,j} \in I_{r,j}$ of r $\in R(j)$ within, $j \in J$ is defined as shown in Equation (6):

$$i_{r,j} = \{i \in I(r,j) : r \in R\,(j) \text{ and } j \in J\} \quad [\#\, injury] \tag{6}$$

Step 4 - Safety screening indicator computation

The literature is quite rich with valuable indicators that can be employed in road safety analysis to evaluate road safety performance, e.g., [12,16,22,39,40]. However, as mentioned in Section 2, European and national recommendations are mostly considered in this work, by developing the road network safety assessment based on crash frequency, severity, and exposure measures. To account for these measures, first, we estimate the social costs (expressed in €) of each crash, which are computed as the sum of road crashes, deaths, and injuries multiplied by the related unit costs estimates. Then, we formulate the Adjusted Accident Cost Rate Index (AACRI) as the ratio between the social costs at a given site over a specified period, and the segment length per the related traffic volume (expressed in veh*km travelled). The potential of such index is twofold: first, being a simple-to-compute indicator, it can be widely accepted and used also among administrators and experts. Second, by returning the safety performances for each path in terms of cost, it provides a first evaluation of how much is paid for unsafety road and, therefore, a criterion to prioritize interventions. Indeed, as road safety interventions to improve road infrastructure safety are usually high resource-consuming, such index can be extremely useful to support the decision-making process.

More formally, let α, β, and γ be the unit cost estimates associated with a road crash [€/crash], a road death [€/death], and a road injury [€/injury], respectively. Then, by combining Equations (4)–(6), the social cost for each path is computed as shown in Equation (7):

$$c_{r,j} = \alpha \cdot n_{r,j} + \beta \cdot m_{r,j} + \gamma \cdot i_{r,j} \quad [€] \quad \forall\, r \in R,\ \forall\, j \in J \tag{7}$$

Next, let f be an adjustment factor that homogenizes the quantities involved into the computation of the crash rate (i.e., the number of days in a year to be considered, e.g., 365, or other values depending on specific prescriptions). By using Equation (2), Equation (3), and Equation (7), the AACRI (denoted by $T_{r,j}$) for each path is computed as shown in Equation (8):

$$T_{r,j} = \frac{10^6 \cdot c_{r,j}}{f * l_{r,j} * v_{r,j}} \quad [\frac{€}{mil\ veh * km}] \qquad \forall\, r \in R,\ \forall\, j \in J \tag{8}$$

It is worth noting that, crashes (road deaths and injuries) are generally expressed on a year-base (i.e., crashes/year), whereas AADT is expressed on a day-base (i.e., vehicles/day). Therefore, if measurement units are not consistent, f must be introduced to amplify the traffic flow time reference into year (i.e., days/year).

Moreover, Equation (8) is for a link (or a segment), not a node (or an intersection). Indeed, the AADTs for an intersection should include both the major and minor roads and there is no segment length. Therefore, in this paper, even if a path consists of several segments and nodes, Equation 8 provides this ratio only for each path.

Finally, besides representing a novel safety metric and including cost criteria in the evaluation of crashes, the AACRI aggregates in one measure the main components of risk, i.e., the frequency of accidents, the exposure measure, and the severity. Specifically, the frequency is evaluated in terms of number of crashes, number of road deaths and number of injuries associated to a single path; the severity is evaluated in terms of social costs for crashes and the exposure is evaluated in term of average vehicle x km for each path.

Step 5 – Road network ranking and maps creation

Once the values of the AACRIs are computed for all the paths, the most critical paths can be ranked according to a specific scale. To our knowledge, there are many methods to develop a ranking scale, and in this study a five-level scale is adopted, based on the distribution quartiles. First, once the $T_{r,j}$ values have been computed for each path, they are sorted from the lowest to the highest. Then, as proposed by [41], thresholds are set based on the lower, the middle, and the upper quartiles (Q1 = 25th percentile, Q2= 50th percentile and Q3 = 75th percentile, respectively) of the related distribution. Next, the interquartile range (IQR) of the distributions of the sorted $T_{r,j}$ is also introduced, to enable the identification of the most critical paths. Usually, the IQR is defined as the difference between Q3 and Q1, and it is generally used to identify and remove outliers from a distribution, as they may affect the findings. To do so, the first and the third quartile are extended by a quantity equal to 1.5 × IQR, respectively, so that a lower and upper threshold can be defined, beyond which the values of a distribution are considered as outliers. Conversely, in this study, the IQR is used to better detail the ranking scale, and emphasise those ‘anomalous’ values, rather than remove them from the distribution. More precisely, the extension of the third quartile above by 1.5 × IQR defines a further threshold, which enables us to enlarge the ranking scale to a five-level scale and identify the highest values of the distribution, i.e., the path with the highest AACRI. Therefore, a new level is defined, with a limit equal to (Q3 + 1.5 × IQR) and the upper limit equals to the maximum value of the distribution. As for the extension of Q1 below by 1.5 × IQR, it does not properly contribute to the definition of a new level of the ranking scale. However, given that $T_{r,j}$ is a non-negative quantity, (Q1-1.5 × IQR) must be higher or at least equal to zero. Although this scale depends on how to define acceptable ranges, one has not to obey the previous indications to use the method, because these ranges can be derived in some other ways.

Table 2 shows the structure of the five-level ranking scale by reporting for each level the related description in terms of unsafety extent (from very high unsafe to safe), the lower and upper limits that define the numerical level of the interval, the related colour for mapping purposes, and the expected action suggested from the road safety Authority. Specifically, the ranking scale should be read as an unsafety scale, thus the lower the AACRI, the safer the path. Therefore, when defining strategies to improve road safety, roads that score an AACRI belonging to the 5th level should be considered as a priority. Indeed, roads in such a range are generally associated either to a high number of crashes occurred or fewer crashes but more severe.

Table 2. Definition of the ranking scale for the AACRI distribution.

Level of unsafety		**Ranges values (AACRI)**		**Expected action**
		Lower limit	**Upper limit**	
5	**Very high**	(Q3 + 1.5 × IQR)	MAX	Urgently proceed with in-depth on-site inspection
4	High	Q3	(Q3 + 1.5 × IQR)	Proceed with in-depth analysis (either on-site or off-site)
3	Medium	Q2	Q3	Plan an inspection campaign
2	Slight	Q1	Q2	Just need to monitor the AACRI over time
1	Low	(Q1-1.5 × IQR)	Q1	No specific need to intervene

Notably, we used the five ranking scales by introducing the IQR of the distribution of the AACRI. The shape of the distribution (symmetric, positively skewed, or negatively skewed) of the study area governs the boundary values of the range. However, this does not imply that the proposed ranking scale is arbitrary. Indeed, whatever the distribution of the values of the AACRI is, one will always be able to identify the related quartiles (25th, 50th, 75th percentiles, and the IQR) and the minimum and maximum values. In other words, the structure of the ranking scale is absolute for any context. Conversely, depending on the characteristics of the crash occurrence in different contexts, the numerical values of the upper and lower limits of each unsafety level can vary. As a result, these values are interpreted as relative values. In doing so, the ranking scale can be applied to each context as it can easily adapt itself on different road crash conditions and enable the identification of the most critical road network sites. Finally, although several roads may exhibit a high risk of crashes, the AACRI is a numerical value. Therefore, it can be sorted in descending order: at the at top, the most critical path is reported.

The expected outcomes of the path ranking are twofold: the first provides a simple and clear dashboard of the screening, where percentages show the share of the total paths belonging to each level of the ranking scale. Hence, LAs and RAs can have a clear picture of the overall safety performance of the road network. The second outcome provides specific maps, where each path is represented with a colour corresponding the related safety ranking level. Maps can be produced in a GIS environment, following the path construction rationale, and uploaded on a territorial information system to be consulted by each administrative and road authority.

As mentioned above, the flexibility of the road network partition here proposed (i.e., path of each road within a specific territorial jurisdiction) enables us to produce RNS at different detail. More precisely, depending on which level of the hierarchical administrative boundaries is considered, the overall computation procedure can adapt itself with respect to the territorial jurisdiction chosen. Indeed, since Equations (3) and (7) return a result weighted over the path length, the path length will vary, as well as the AADT and the number of crashes, depending on the territorial boundaries considered. For instance, if municipalities are chosen as territorial jurisdiction, the procedure will return for each path with an AACRI weighted over the municipality's boundaries. Similarly, if provinces are chosen as territorial jurisdiction (and provinces include a set of municipalities), the procedure will return an AACRI for each path weighted over the provincial boundaries, thus providing a unique value without distinguishing by municipality.

4. Real-World Application

4.1. Case Study

The road network of the Lombardy Region (LR), Italy was investigated as a case study, to apply the operational framework. The LR is the most populated region in Italy (10+ million inhabitants), and it is considered the commercial and industrial hub of the entire country, as well as one the most important in Europe. LR covers a strategic position and includes parts of three of the main TEN-T corridors (i.e., the Mediterranean, Scandinavian-Mediterranean, and the Rhine-Alpine corridors) with great traffic volume. The regional road network is one of the wider and denser in Italy and it comprises 700+ km of motorways, 10,000+ km of provincial roads, and about 1,000 km of state roads, besides 58,000 km of local roads. Therefore, it plays a crucial role in the international and national transport network. Nevertheless, LR yearly records 30,000+ road crashes, 400+ deaths, and 40,000+ injuries, which is one of the highest records in Italy. To summarise, LR is like several European and Italian regions, apart from being very large in terms of implementation scale and representativeness. Hence, this application provides an interesting case study of RNS from which lessons can be learnt for other similar European regions. For the sake of space limit, this study will focus on the main non-urban road network of the LR. Figure 3 shows the overview map of the road network selected as the case study, which is blue-edited.

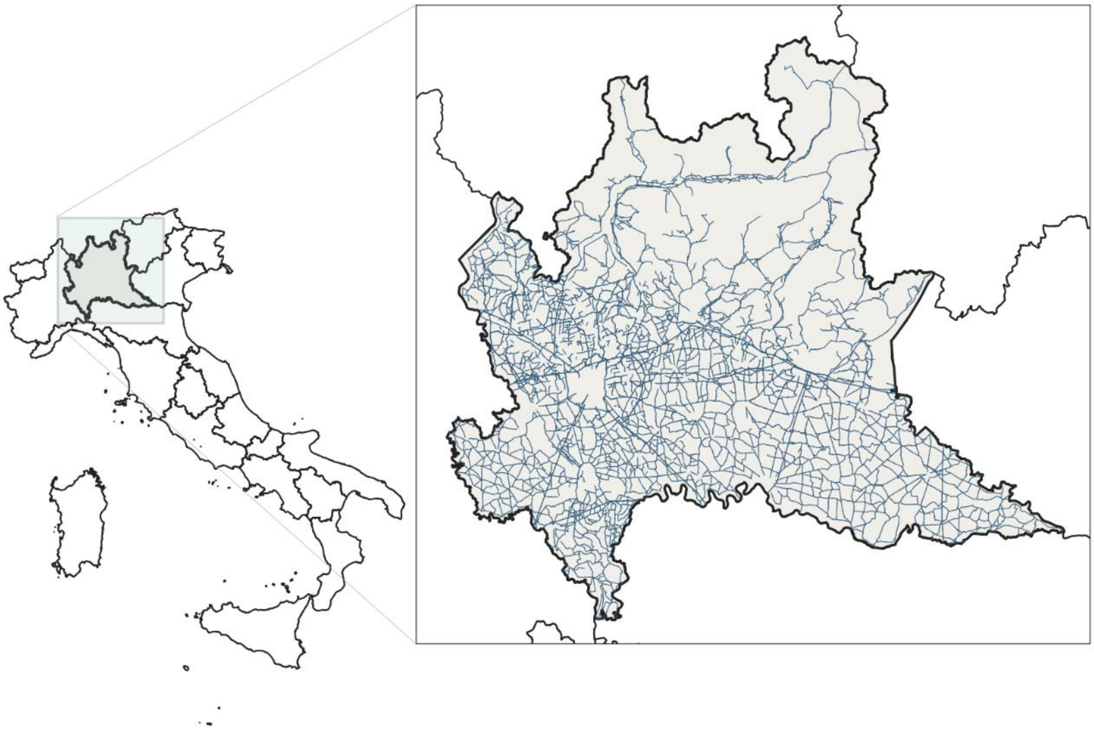

Figure 3. Map of the main road network of the Lombardy Region.

4.2. Applicative Setup

Base maps data were retrieved from the open-access regional topographic database in a shapefile format. Administrative boundaries of the several NUTS, i.e., the whole region, provinces, and municipalities were gathered.

Traffic data were provided by the Regional Directorate General (DG) for Road Safety. Over the years 2016–2018 the LR puts a major effort towards the development of the regional O/D matrix to model the AADT of the overall road network. The dataset was provided in a shapefile format, and it comprised the representation of the road network, based on a node-link structure. Each link was assigned with the road name, road type, and the AADT.

Crash data occurred in RL over the five-year period 2014–2018 were provided by Polis-Lombardia, the Regional Institute for Policy Support. Non-public data were provided in the spreadsheet format and reported all the main variables collected by the national statistical road crashes template. Specifically, crash data and location (i.e., province and municipality NUTS codes, route name or code), road type, location attributes (e.g., segment and/or intersection type, pavement type), number of people involved are included in the template. As for crashes location, 21% of the record missed of plane or geographical coordinates and others reported them inaccurately.

Before applying the framework, some data cleaning and mis-recording rectification were performed both in the crash and traffic data, to make information consistent in the content and homogeneous in the format among the several data sources (e.g., fix road names or code). This task was crucial for the framework to run properly. A total of 34,000+ crashes and 24,000+ road segments were included in the analysis.

4.3. Framework Development

In this sub-section and in the next section, the results obtained are briefly presented and described. More precisely, Step 1 was performed in a GIS environment, given that the traffic and geographical basemap data were available in a shapefile format. The open access QGis software was used. Steps 2, 3, 4, and 5 were performed in MS Excel, as formula computation was easier to perform there. Finally, step 5 was also refined in QGis for map creation and visualisation.

To define the road network paths, according to Equation (1), road names and municipalities NUTS were considered in this work. From a practical perspective, to make Equations (2) and (3) easier to compute, path codes were created into the road network basemap, by simply merging the variable "road code" and "NUTS" of the data source for each segment of the network. In such manner, each segment was attributed a new variable, which indicated the path association. Although not exhaustive, Table 3 provides an example for the paths' definition of the A4 Turin-Venice motorway (road code "A04"). More precisely, each segment s of the motorway is associated to the related path code, defined according to different jurisdictions levels, i.e., municipalities, provinces, and the whole region. NUTS of the different jurisdictions are identified by a 5-digit code (e.g., "17029") and a 2-digit code (e.g., "17") for municipalities and provinces, respectively. The NUTS code for the region was not assigned, as it represents the study area, hence each road is considered.

For the sake of clarity, at the municipality level, the segments "41681" and "43981", as well as other segments (i.e., "…") which are not reported here due to space limitation, belong to the path of the A04 motorway within the jurisdiction of the municipality "17029", coded as "A04_17029". Likewise, segments "40249" and "41641" belong to the path coded as "A04_17127". If the provincial level is considered, such paths will be included within the path related to the higher level of the province jurisdiction, thus the path is coded as "A04_17". If the regional level is considered, those paths will be included within the path related to the higher level of the province jurisdiction, thus the path is coded as "A04".

Table 3. Path definition for the A4 Turin-Venice motorway (Italy) for different jurisdiction levels (i.e., municipality, province, region).

Path codes for each jurisdictional level			*s*-segment
Regional path	**Provincial path**	**Municipality path**	
A04	A04_17	A04_17029	41681
A04	A04_17	A04_17029	43981
A04	A04_17	A04_17029	…
A04	A04_17	A04_17127	40249
A04	A04_17	A04_17127	41641
A04	A04_17	A04_17127	…
A04	A04_17	…	…
A04	A04_16	A04_16051	31690
A04	A04_16	A04_16051	32118
A04	A04_16	A04_16051	…
A04	A04_16	A04_16037	32117
A04	A04_16	A04_16037	32146
A04	A04_16	A04_16037	…
A04	A04_16	…	…
A04	…	…	…

The dots ("…") stand for the other segments (and path codes) which belong to the same path but are not reported here due to space limitation.

A set of more than 400 paths was obtained, with a length ranging from 0.10 km to more than 30 km and more than 97% of paths being up to 7 km. Such path lengths can be considered appropriate for RNS, as the EuroRAP procedure indicates a length range of 5–10 km [22]. This was also confirmed by other research from the international perspective [42,43].

Once the paths were defined, the length, the AADT volume, and the number of crashes, deaths and injuries were computed for each path, according to Equations from (2)–(6).

Then, to compute Equation (7), crash cost estimates provided by the Italian Ministry of Transport were used [43]. Specifically, the MIT method is based on the Human Capital approach [3]. It considers the following components in the computation: human costs (i.e., production loss and medical costs) and general costs (property damage, administrative costs), while no human damage cost is considered. As a result, the method returns a crash average cost based on the severity of the crash itself. Table 4 reports the quantitative economic evaluation resulting from the implementation of such method.

Table 4. Road crash, death, and injury cost estimates [43].

Cost unit estimates items	Cost estimate [€]
Average road crash cost (α)	10,986.00 €
Average human road death cost (β)	1,503,990.00 €
Average human injury cost (γ)	42,219.00 €

Finally, the AACRI was returned for each path, by applying Equation (8). Specifically, the computation of the AACRI was performed separately for motorways, state roads, and provincial roads. Their selection was mainly based on the administrative road classification, as insufficient information on the functional attributes (e.g., operating and design attributes) were included in the road data source. It is worth noting that state roads were separated from provincial roads because they are managed by different road authorities and for their different relevance in the whole road network (i.e., state roads have a national relevance as opposed to provincial roads).

4.4. A Numerical Example

To clarify the computation of the AACRI, a numerical example is provided in what follows. The case of the A1 Motorway is shown, considering the six municipal jurisdictions it crosses within the boundaries of Province of Milan, in the LR.

To compute the social costs for each path of the A1 Motorway, Equation (7) is applied as follows:

- the values included in columns (c) of Table 5 are multiplied by the crash average cost α of Table 4;
- the values included in columns (d) of Table 5 are multiplied by the average human road death cost β of Table 4;
- the values included in columns (e) of Table 5 are multiplied by the average human injury cost γ of Table 4;
- the $c_{r,j}$ is the sum of all the values computed for each row. Results are shown in Table 6.

Table 5. Data related to the A1 Motorway.

Paths	Path length - $l_{r,j}$ [km] (a)	Traffic volume - $v_{r,j}$ [veh/day] (b)	No. of crash (c) - $n_{r,j}$	No. of deaths (d) - $m_{r,j}$	No. of injuries (e) - $i_{r,j}$
A01_15071	6.68	44,927	4	1	9
A01_15140	2.33	51,298	7	1	10
A01_15146	1.27	36,567	1	0	1
A01_15192	5.35	42,030	8	1	9
A01_15195	12.8	46,170	29	1	48
A01_15202	6.38	45,172	10	0	19

Table 6. Computation of the social cost for A1 Motorway.

Paths	$\alpha \cdot n_{r,j}$ [€]	$\beta \cdot m_{r,j}$ [€]	$\gamma \cdot i_{r,j}$ [€]	$c_{r,j}$ [€]
A01_15071	43,944	1,503,990	379,971	1,927,905
A01_15140	76,902	1,503,990	422,190	2,003,082
A01_15146	10,986	0	42,219	53,205
A01_15192	87,888	1,503,990	379,971	1,971,849
A01_15195	318,594	1,503,990	2,026,512	3,849,096
A01_15202	109,860	0	802,161	912,021

Next, the AACRI can be computed by applying Equation (8) and using for *f* the value 365 day/year. Results are shown in Table 7.

Table 7. Computation of the Adjusted Accident Cost Rate Index for A1 Motorway.

Paths	**Social costs** $c_{r,j}$ **[€]**	**Path length** $l_{r,j}$ **[km]**	**Traffic volume** $v_{r,j}$ **[veh/day]**	$T_{r,j}$ **[€/mil-veh×km]**
A01_15071	1,927,905	6.68	44,927	17,599.85
A01_15140	2,003,082	2.33	51,298	45,914.46
A01_15146	53,205	1.27	36,567	3,138.82
A01_15192	1,971,849	5.35	42,030	24,025.23
A01_15195	3,849,096	12.8	46,170	17,844.16
A01_15202	912,021	6.38	45,172	8,670.06

5. Results and Discussion

Figure 4 shows the road network safety performance dashboard, for the whole network and for each road class. It reports the percentage of paths belonging to each level of the ranking scale at the regional level (i.e., considering all the path over the regional jurisdiction). As for the whole network, 50% of paths belongs to the lower levels of the ranking scale, i.e., level 1 (25%) and level 2 (25%), thus 50% of the whole network can be considered as sufficiently safe. A 25% of the network belongs to the intermediate level, i.e., level 3, whereas 19% and 7% belongs to level 4 and level 5, respectively.

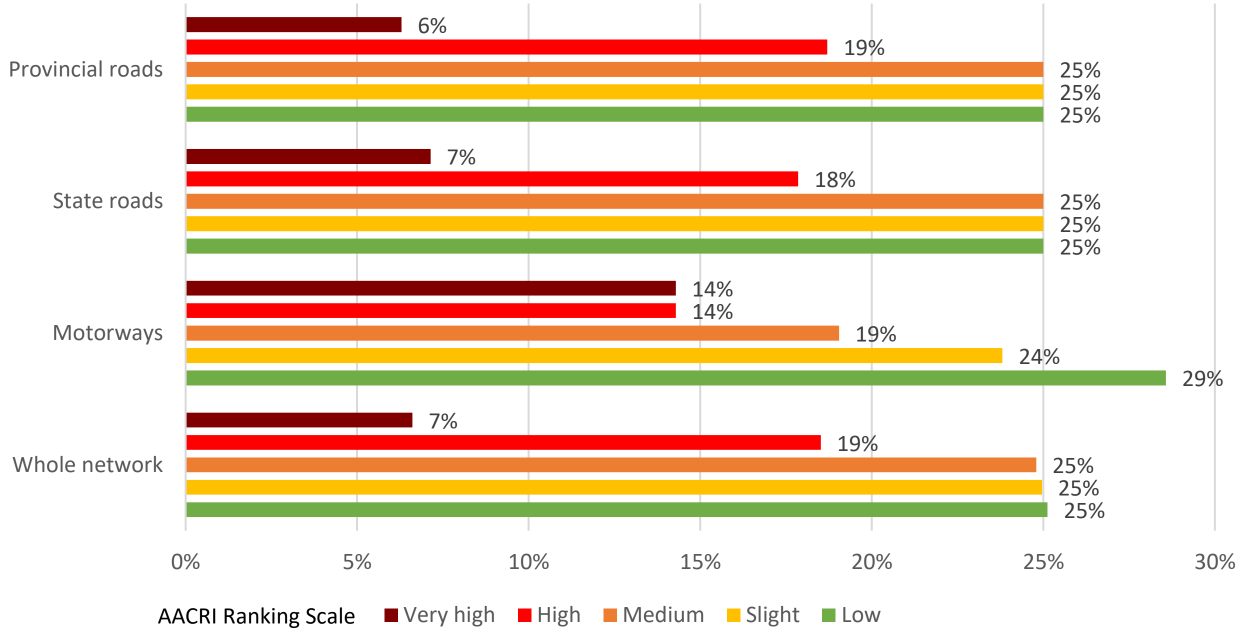

Figure 4. Road network safety performance dashboard. Share of paths within the different ranking levels based on the AACRI values**.**

Some differences can be found at the different road categories and focusing on the most critical crash rate ranges (i.e., level 4 and 5). Motorways have the highest share of level 4 and level 5 AACRI (28% overall) compared to Provincial and State roads (25%), and they have the highest percentage of paths showing a level 5 AACRI (14%), compared to provincial roads (6%) and State roads (7%). However, with the motorway being the highest road class (and those that play a crucial role in the European TEN-T network), and with high volume traffic and specific design characteristics, higher safety and design standards are usually required for them. Motorways management is run by dedicated road agencies and maintenance is usually regular and specific monitoring and intervention procedure are in force for such roads. Moreover, toll incomes help in road management. Conversely, State and Provincial roads networks are wider, and they are managed at national and local level, respectively, and by different road authorities. Therefore, as public resources are scarce, interventions are less easy to be performed in time. Therefore, the LR should consider separately such road classes, and prioritize the ones managed by public bodies. Then, the selection of the most critical road should be made considering the AACRI results.

Figure 5 shows the maps representing the main screening of the non-urban road network, and specifically they refer to the regional level (i.e., all the paths are evaluated over the regional jurisdiction). For sake of clarity, maps are shown separately for motorways (Figure 5a), State Roads (Figure 5b), and Provincial Roads (Figure 5c). These maps show road screening results as they enable us to immediately identify which are the worst performing roads (red and dark red ones) and which roads they are.

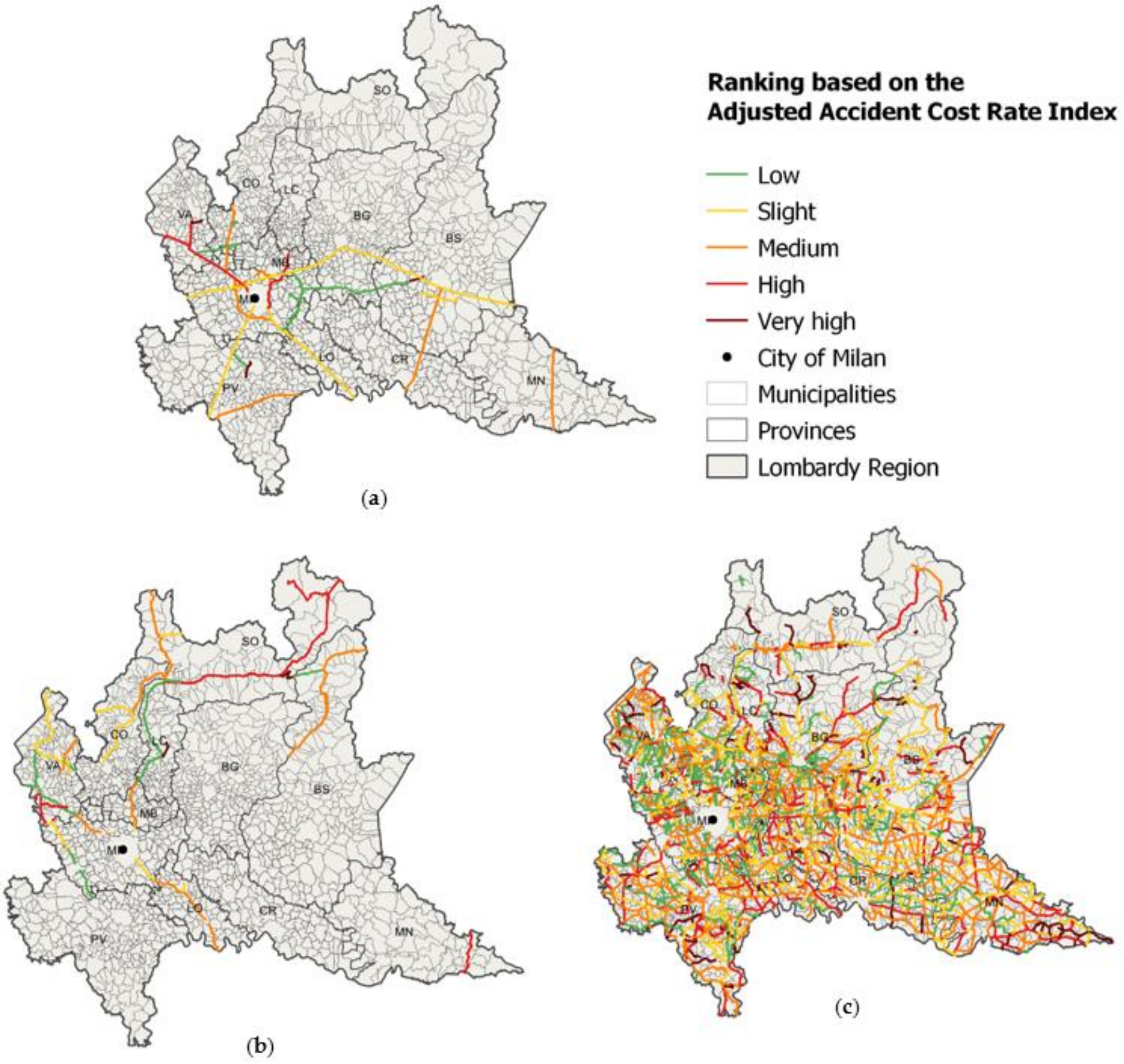

Figure 5. Road safety network screening maps of the entire main non-urban network at the regional level: (**a**) motorways, (**b**) state roads, and (**c**) provincial roads. The label in all maps represents the province code.

Figure 6 shows the capability of the framework to adapt itself at different levels of screening, thus at the regional (i.e., entire routes within the regional boundaries), provincial (i.e., routes within the provincial boundaries), and municipality level (i.e., routes within the municipalities boundaries). For the sake of clarity, results are reported for the motorway network only. In these maps, jurisdiction boundaries are reported to emphasise the screening capability of such procedure. In Figure 6a, the screening at the regional level is represented. In this case, the paths are defined considering the whole regional jurisdiction, hence the path corresponds to the overall road. At such screening level, independently from the provinces or municipalities traversed, the AACRI is computer weighted over the route. For instance, the A04 motorway is represented by the yellow line that runs from East to West, in the middle of the region. Considering such route at the regional level, a medium level of AACRI is registered. In Figure 6b, the screening at the provincial level is represented. In this case, the paths are defined considering the provincial jurisdictions, hence different values of the crash cost rate are computed for the same route depending on the province at hand. As for A04 motorway, now different colours (i.e., AACRI ranges) are shown, depending on the province considered. Starting from East, the A04 in the Province of Brescia (BS) shows a low level of AACRI (i.e., green edited path). While approaching to the West, the AACRI increases (and colours accordingly) up to medium in the provinces of Bergamo (BG) and Monza-Brianza (MB), respectively, and medium-high levels in the province of Milan (MI). As for Figure 6c, the screening at the municipality level is represented. Each route is partitioned based on the municipality boundaries and the AACRI is computed within the municipality jurisdiction, for each path (best shown in Figure 6c zoom).

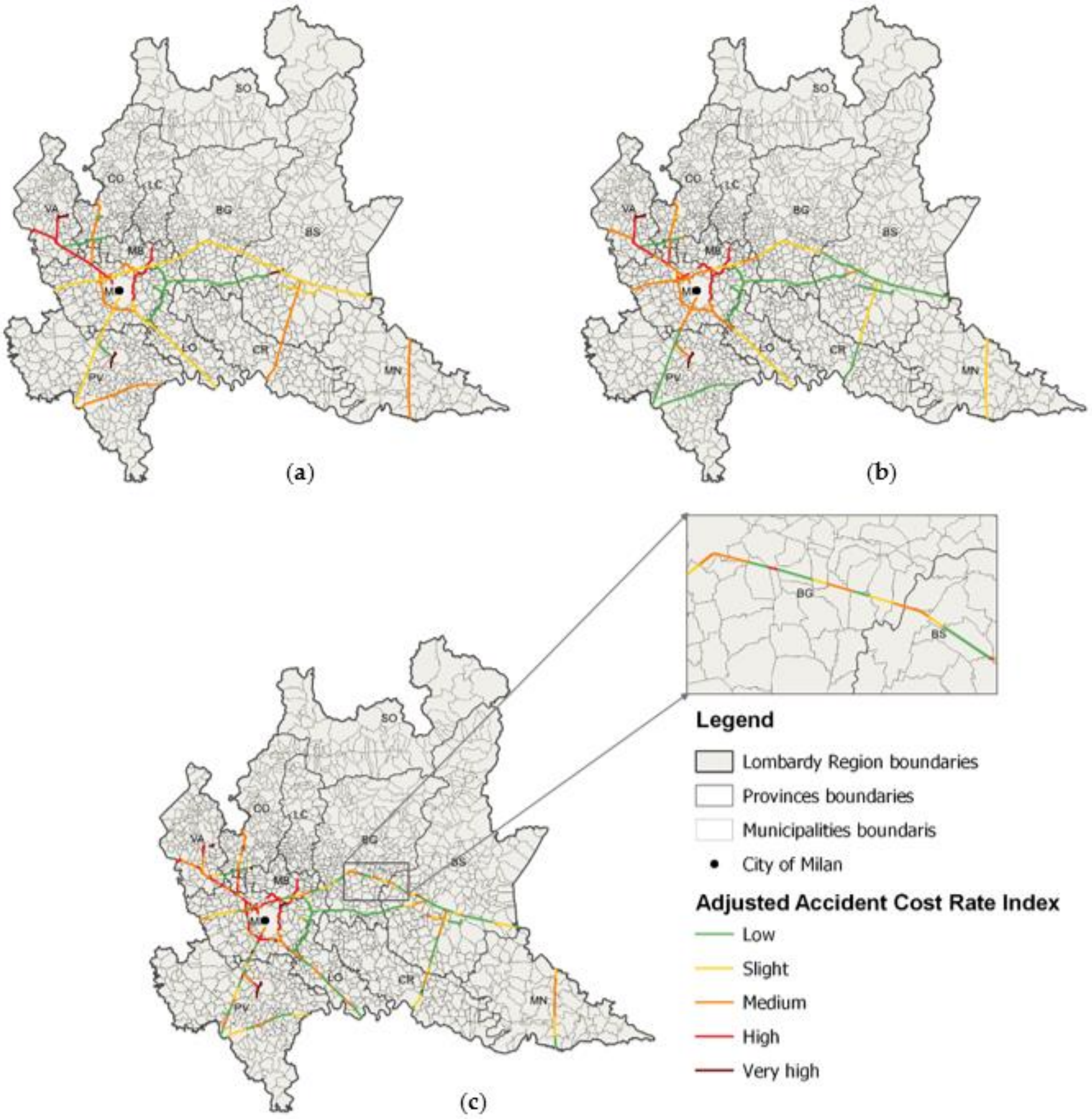

Figure 6. Road safety network screening maps of the motorway network over different jurisdictional level: (**a**) regional level, (**b**) provincial level, and (**c**) municipality level.

Such flexible structure enables a road network screening at a both wider and in-depth level. More precisely, given the need to prioritise interventions and the scarcity of resources to implement them, such flexibility can help in several cases. For instance, when considering the whole network (or a specific road class), once the most critical routes have been identified, investigation can be conducted at a more detailed level to highlight the most critical section of the most critical route. Furthermore, if the network screening is conducted within a defined area (e.g., municipality), such flexibility can help detect the most critical paths among several routes that cross a given jurisdiction.

6. Conclusions and Research Perspectives

Despite improvements that have been registered over the last decade, road safety Europewide still represents a major social and health issue to be overcome; we cannot deal with sustainable mobility without considering road safety as a crucial facet. The implementation of Road Infrastructure Safety Management System (RISMS) procedures is fundamental for road authorities and local administrators, responsible for road safety to assess road network safety performance and plan interventions. Therefore, providing them with effective tools to perform safety performance evaluations would enhance their monitoring capabilities. Specifically, road network screening (RNS) is the first stage of the entire RISMS procedure, and it is aimed at detecting the most critical routes in terms of road crashes. RNS is not a novelty in the transportation community since many RNS models and methods exist. On the one hand, most of the literature have focused more on modelling improvements rather than data processing and management. However, processing and management are crucial when issues on data availability and quality persist. In addition, it has required the formulation of fundamental assumptions regarding the probability distribution for crashes counting as well as the functional specification of the several variables. On the other hand, RNS methods were proposed by several national safety guidelines. These methods are straightforward, but they require accurate crash location, adopt partial index for black spot identification and present results by fixed maps.

This paper covered these gaps by integrating existing techniques and tools into an operational framework to perform RNS. More precisely, this study improved the state of the art by:

- Handling crash location data without using plane and/or geographical coordinates, because crash-coordinate data are still missing or poorly recorded in many countries.
- Adopting other location attributes to associate the crash and related traffic data and base map attributes to a road segment. Although this new way to 'localise' crash data needs for a new segmentation type named 'path' (i.e., the portion of a generic road within the boundaries of the lowest territorial jurisdiction at hand), it aims to provide a more accurate screening of the network, because all crashes data are considered.
- Proposing a simple, but complete Adjusted Accident Cost Rate Index. Besides representing a novel safety metric and including cost criteria in the evaluation of crashes, this index aggregates in one measure the main components of risk, i.e., the frequency of accidents, the exposure measure, and the severity. Although this index is not being able to account for the regression-to-the-mean bias, it was introduced because it is easy to understand, simple to interpret, and straightforward to assess using basic statistics.
- Enabling a general and multiple-level network screening, since the computational process can adapt itself, depending on the territorial jurisdiction considered (e.g., regional, provincial, and local scale): the crash rate values are shown by GIS variable maps at different administrative levels.

To the best of our knowledge, this framework provides the first empirical contribution towards the road network safety screening while processing incomplete and/or inaccurate crash data.

Relevant implications in the use of this framework are as follows:

- The framework is based on an easy-to-implement five-steps procedure for the RNS, when poor data quality occurs. This enables a high degree of replicability and adaptability above all practitioners that often presents uncertainties and inaccuracies on plane and/or geographical coordinates for crashes.
- The 5-level ranking scale built according to the novel safety metric enables a clear identification of the most critical paths, and this is essential to direct strategies and allocate funds more efficiently.
- The road network screening at different administrative levels enables road authorities and administrations to approach the network they manage differently. Thus, the path is referred to the regional, provincial, or local level. In addition, given the rationale of the entire process, it can be intended as a "black spot" identification procedure, in that it enables us to quantitatively highlight the paths with the highest social-cost burden (thus it also returns an economic appraisal) that the number of road crashes that have occurred have produced. Indeed, the proposed screening is like a typical "black spot" identification, which is conducted by a jurisdiction to identify the "high crash locations."

- The procedure, coherently to each screening process, enables us to allocate resources more efficiently as in-depth analysis about the causes of such low safety performance can be focused on those most critical paths. Then, e.g., infrastructural layout, environmental factors, or traffic components can be further investigated to identify issues (e.g., presence of several intersections and quite heavy freight vehicles) and define how to intervene, e.g. [44,45].

The whole procedure was applied to the main non-urban road network (i.e., motorways, state roads and provincial roads) of the Lombardy Region, and it was found that more than half of the network resulted in being quite safe.

Further research can be developed to improve this framework. First, different indicators (e.g., dead and/or injuries per length unit or traffic volumes) and even the most advanced models can be chosen to evaluate the safety performance of the road network. For instance, an adjusted accident cost rate index was computed in this framework, which disregards the non-linear relationship that exists between crash occurrence and traffic volume. Nevertheless, a bivariate (frequency and severity) risk crash model with all available road factors and exposure factors will be formulated and developed, to provide a more refined crash risk indicator as it has been done in public transport, e.g., [46–48]. Second, the overall structure and the path definition can be further improved to account for different data sources and attributes to be included in the evaluation. Third, the whole procedure can be automatised, so that the computation process would be less time consuming. Fourth, data for this application were available before the COVID-19 pandemic. An interesting challenge will be an analysis and comparison referred to the *pre* and *post* pandemic safety conditions. Finally, the speed was shown a crucial issue in the crashes' occurrence in some provinces of LR [49]. Thus, considering the speed as a variable to be included in the adjusted accident cost rate index could be a new issue to investigate in the future.

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