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Mega-Events: Assessing Road Safety through an Operating Framework. An Application for the Milano–Cortina 2026 Winter Olympic Games †

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Abstract: To meet the United Nations and European Union goals of reducing road crash fatalities and injuries, it is also relevant to address the negative externalities due to mega-events on the road network and the local communities, to assess the safety of the road network involved, and to implement appropriate measures for different road environments. Despite their relevance, the literature often overlooks social costs and risks associated with mega-events. This study presents an operating framework for rapidly assessing the safety of the Milano–Cortina 2026—"*Via Olimpica*" road—which will host a significant proportion of the traffic during the Winter Olympic Games in 2026. The framework proposes a simplified Road Infrastructure Safety Management (RISM) to address the unique challenges posed by the limited time available for screening and implementation by local authorities. The framework integrates four data sources and follows a seven-step procedure. It provides recommendations for improving road safety by identifying critical road sections and blackspots. Road authorities, practitioners, and public administrations may all benefit from the framework, as it makes it easier to prioritise safety improvements within time constraints.

Keywords: road safety; mega-events; infrastructure risk assessment and management; RISM; RNS; road infrastructures; accident cost rate index; SDG; road environments; road operating speed

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1. Introduction

In the definition of the Sustainable Development Goals (SDGs), the United Nations (UN) has recognised that part of the path to achieving greater mobility sustainability is through the improvement of road infrastructure safety. Specifically, Target 3.6 has been identified as a goal to halve global road deaths and injuries by 2030 [1]. Globally, remarkable achievements have been made but, despite this, the problem is still highly relevant, with 1.19 million deaths in 2021 (−16% compared to 2016) placing this cause of death 12th globally and 1st for people aged 5–29 [2,3]. In addition, road crashes have an impact in terms of social costs that range from 0.4% to 4% of the national Gross Domestic Product (GDP) in different European countries, with an average of 1.76% [4,5]. Expenditures incurred by the community could be used more efficiently to prevent the social damage inflicted by this phenomenon by financing in-depth analyses and improvements in road safety [6].

Despite the EU's commitment to achieving SDG Target 3.6, the interim goal defined between 2010 and 2020 (reduction of 50%) still needs to be achieved Europe-wide [7,8]. Data indicates a pace reduction of progress in decreasing fatality rates in recent years. The average reduction in deaths between 2011 and 2021 was 31.33%, with some countries like Norway surpassing the 50% target and others like Romania slightly exceeding the 10% threshold. Italy falls in the middle with a reduction rate of 26.35%, placing it below the European average [9].

Mega-events are large-scale sporting and/or cultural events with an (inter)national profile and influence, organised on a bigger scale than regular sporting matches, have significant impacts on the built environment and the population, and come with high costs. The Olympic Games are the highest example of the mega-event in sports [10,11]. The magnitude of these events led scholars and governments to assess the extensive risks, externalities and benefits associated with them to estimate before and after effects and their overall relevance in terms of sustainability [12,13]. The most common subjects examined are socio-economic impacts, tourism, heritage, image, media, hygiene, urban transformation, and cultural and environmental effects. Specifically, more subjects, such as inclusion and diversity, sports participation, accessibility, disaster preparedness, social cohesion, civic pride and social capital, have been examined [12,13]. However, in the literature regarding sporting events, the significant risks and social costs associated with the increased traffic and vehicular crashes are often overlooked and only Jakar et al. [14], Redelmeier and Stewart [15] and Wood et al. [16] deal with the relationship between sport events and increased reported vehicular crashes. Moreover, none specifically deals with the relationship between mega-events and vehicular crashes. Using longitudinal data from Cleveland, Ohio (2017–2019), Jakar et al. [14] examined the relationship between professional sporting events and vehicle crashes by exploring crash data, game times, and venues. Employing two multivariate modelling analyses, they established the spatial and temporal relationship between multiple sporting events (i.e., National Football League, Major League Baseball, and National Basketball Association events) and vehicular crashes with the scope of providing the city with relevant policy information on how to achieve its "Vision Zero" goal on traffic fatalities and injuries. In the United States, Redelmeier and Stewart [15] investigated whether a mega-event such as the Super Bowl impact traffic fatalities. They looked at 27 Super Bowl Sundays and found a 41% relative increase in the average number of fatalities after televised games. The increase in fatalities was evident in 21 of the 27 years and accounted for an average of seven additional deaths compared with the average control Sunday. Wood et al. [16] investigated the possible relationship between spectator alcohol consumption, vehicle collisions and "good" top basketball and football games, as measured by the closeness of the score. The closeness of the score at the venue was positively associated with the number of deaths on the day of the game for a given event; games with closer scores resulted in more traffic fatalities than "blowout" games.

Although the present literature still fails to establish through extensive studies a strong cause-effect relationship between the hosting of mega-events and the increase in vehicular crashes, some indications have emerged to this extent. These events exert relevant pressure on existing road networks. The potentially disruptive effect of a road crash on an already stressed road network, as well as the magnitude and tragic nature of the social cost that road crashes carry should lead decision-makers to apply a precautionary principle when implementing RISMS that are resilient to adverse events that may occur. This will help to minimise negative externalities, while posing a threat with its allocation of funds and political attention, the exceptionality of these events, presents an opportunity to improve road safety infrastructure, which can have a lasting impact and helps reduce road crashes during the mega-event and in the following years.

The 2008/96/EC directive [17] introduced the Road Infrastructure Safety Management Systems (RISMS) to set a common ground for road safety management at the European. They are a managerial tool used to evaluate safety performance, identify safety problems, and track safety improvements' effectiveness over the entire life cycle of road infrastructures.

With these tools, road authorities can assess the road infrastructure's safety performance and implement safety measures to reduce potential road crashes [18,19]. These methods are analytical tools implementable by governments to identify emerging safety hazards, determine hazardous areas within the road network, identify the main causes of collisions and injuries, and estimate the potential impacts of inclusive and targeted road safety initiatives [20]. RISMS adoption is mandatory for roads within the TEN-T network and recommended for roads categorised as primary in Member States' national networks [19,20]. Road Network Screening (RNS) has been defined as the initial stage of the RISMS approach. RNS is utilised on a broad scale to evaluate overall network safety and identify high-risk roads or areas. It is a preliminary evaluation followed by an extensive investigation to address specific issues and find the appropriate solutions [21].

According to Bonera et al. [6,22,23], the RNS methods frequently utilised for deploying RISMS may be divided into two main categories, each with its own set of challenges. The first category contains advanced mathematical models that which demand specialised expertise for specification, calibration, validation and interpretation [6,24]. These models can be challenging for practitioners since they frequently need particular software or programming abilities and rely on large amounts of data [25]. The second category includes simple or composite indices (e.g., crash frequency, crash rate) that highlight underperforming portions of the road network [26]. However, methodological difficulties such as data availability, processing, and integration with other data sources remain unsolved for these indexes. Data misrecording and misreporting issues exacerbate the applicability and repeatability of these methodologies [27].

The quality and availability of location crash data remains a challenge in many contexts [28–30]. This limitation poses challenges to the localization of crashes, which is partially addressed in Bonera et al. [6,22,23]. The literature has shown interest in assessing the consistency of data collected by law enforcement agencies [31,32]. In particular, it has focused on studying frameworks to improve the localisation of these data by using other information available in crash reports, such as address, street name, and intersection classification [33–35]. One main criticism of these frameworks is that they can be time-consuming and may not be suitable for analyses within a limited timeframe. Using kilometre marker data, which is highly present in law enforcement databases, can address this limitation. According to authors' knowledge, a methodology that uses GIS software to locate existing crashes through the association with a set of digitally reconstructed high-precision hectometres has been found missing in the present literature.

As previously shown, RISMS and RNS are topics that are present and common in the current state of the art in road safety. However, the literature overlooks the risks and social costs associated with increased traffic and vehicular crashes within a limited timeframe due to sporting and mega-events [14–16,36].

This study aim is to develop a framework to help decision-makers in identify high-hazard roads and select feasible and relevant measures to prevent road crashes, fatalities, and injuries in an increased-risk scenario. This framework builds upon [6,22,23]. However, the framework has been expanded (i) to include a crash geolocation process, (ii) to take operating speed into account when investigating crash causes, and (iii) to recommends specific measures for mega-events where time for investigation and implementation is limited (e.g., Olympics, EXPO, FIFA World Cup, music festival). The framework's effectiveness was demonstrated by analysing the SS 36 and the SS 38, known as the "Via Olimpica". In addition, comparisons were made with existing studies to show the viability and applicability of the proposed framework. Consequently, this research seeks to contribute twofold to theory and practical application. From the theoretical perspectives, it introduces an innovative and adaptable rationale for connecting data from diverse sources, a key factor in conducting thorough and impactful road safety analyses, specifically for mega-events. From the practical perspective, this research could assist in the assessment of the overall safety performance of the road network, determining priority actions, and guiding subsequent necessary analyses more cost-effectively.

The remaining paper is structured as follows. Section 2 outlines the framework for assessing road safety and operating speed, georeferencing road crashes and proposing possible remedial measures. Section 3 presents the experimentation on the Milano–Cortina 2026 Winter Olympics Road case study and discusses the results. Section 4 presents research perspectives and conclusions.

2. Data and Methods

The framework includes four data sources and follows three stages and seven steps. It integrates the methodologies previously introduced in Bonera et al. [6,22,23] regarding RNS (Steps 1 and 2), and Martinelli et al. [37,38] regarding the computation of operating speed (Steps 4 and 5). These are further integrated with a novel approach to RISMS (Steps 6 and 7) and road crash georeferencing (Step 3) to map criticalities and propose potential countermeasures. Figure 1 provides an overview of the framework's layout, which is further explained in what follows.

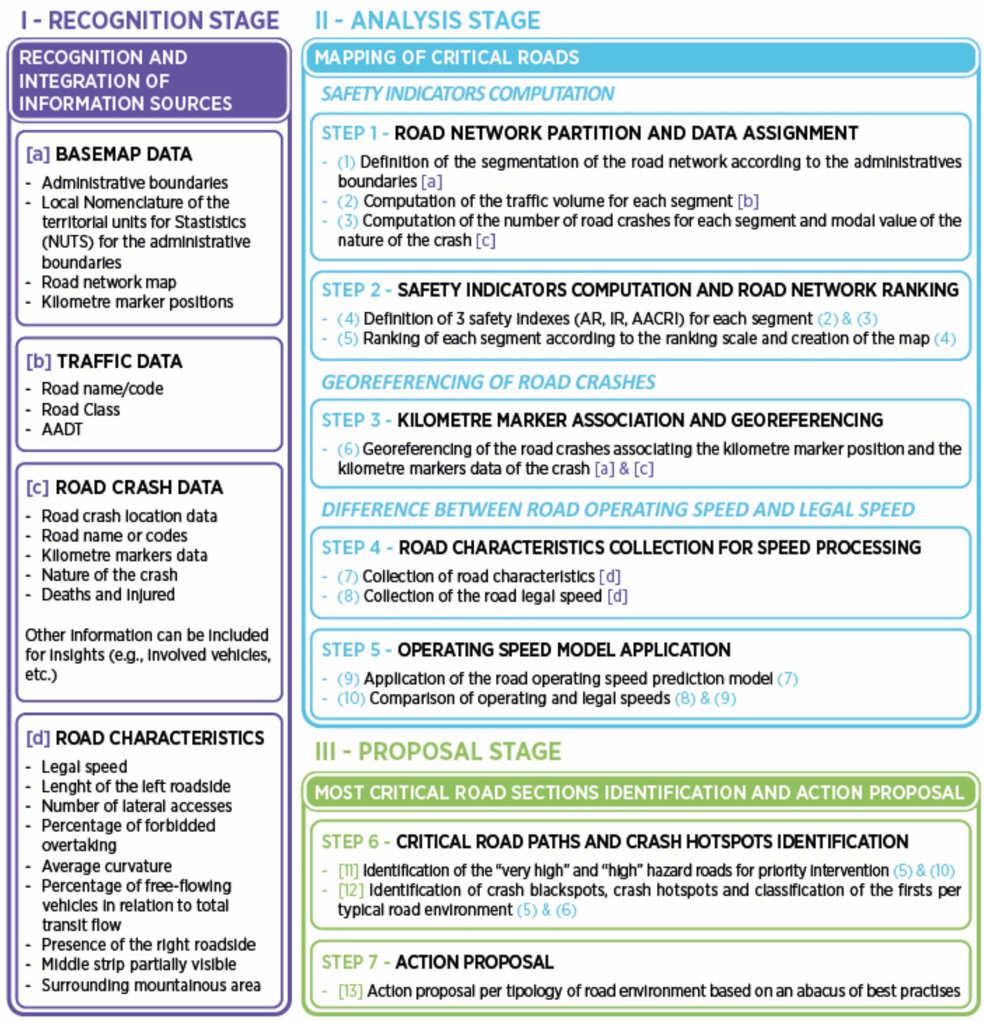


Figure 1. Operating framework scheme.

2.1. I—Recognition Stage

The first Stage consists of data collection from various data sources. It includes (a) base map data (kilometre marker position, main maps, GIS-based data), (b) traffic data (road identification and traffic volume), (c) road crash data (crash events, fatalities, injuries), and road characteristics for fixed length segments (crash events, fatalities, injuries), and (d) road characteristics for fixed length segments (legal speed, roadside length, lateral accesses, overtaking percentage, road curvature, free-flowing vehicles, roadside presence, middle strip visibility, mountainous area); refers to the purple section of Figure 1.

These data are essential for computing safety indicators, operating speed, and comparing the latest with legal speed. If specific datasets are unavailable, data can be collected through on-site and/or off-site visits. Since all data could be supplied in different formats, some preparation would be needed to refine them and guarantee their consistency for the framework's subsequent Steps.

2.2. II—Analysis Stage

The second Stage entails computing safety indicators, operating speeds, and georeferencing road collisions (refers to the heavenly section of Figure 1). By integrating numerous measures of traffic collision exposure and frequency, the technique minimises mistakes in the geographic location of crash events. It enables quick and precise identification of critical crash sections and blackspots. Therefore, it considers time constraints.

2.2.1. Step 1—Road Network Partition and Data Assignment

Steps 1 and 2 perform the RNS methodology introduced in Bonera et al. [6,22,23].

The road safety data, such as crashes and road attributes, are expressed using specific spatial units. The "least common multiple" of the location attributes among all data sources is identified to partition the road network and assign crashes. This involves identifying the common attributes among the data sources, such as territorial jurisdiction and road name or code. The partitioning creates segments of roads within the boundaries of all the territorial jurisdictions from the highest to the lowest, enabling for detailed analysis of each road based on the interested jurisdiction. The denser the network partition, the more accurate the RNS. The denser the network partition, the more accurate the RNS. Formally, let:

- J be the set of territorial jurisdictions in the study area and $j \in J$ be a generic jurisdiction.
- $R(j)$ be the set of roads crossing the jurisdiction $j \in J$, and $r \in R(j)$ be a generic road.
- $S(r,j)$ be the set of the segments of the road $r \in R(j)$ withing $j \in J$, and $s \in S(r,j)$ be a generic segment.
- $P_{r,j}$ be the set of paths formed by all segments $s \in S(r,j)$ of the road $r \in R(j)$ within $j \in J$, and $p_{r,j} \in P_{r,j}$ a generic path.

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

The association of road traffic and crash attributes is essential after the road network partition has been established to consider almost all road crash frequency and exposure measures. Since these attributes are reported on a segment-node basis, each segment is assigned its length and the related Average Annual Daily Traffic (AADT). Next, the length and AADT of $p_{r,j} \in P_{r,j,}$ can be easily computed as the sum of the length and AADT of each segment of $s_{r,j} \in S_{r,j}$, respectively.

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 ($l_{r,j}$) of the path $p_{r,j} \in P_{r,j}$ of $r \in R(j)$ within, $j \in J$ is defined as:

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

The AADT (i.e., $v_{r,j}$) of the path $p_{r,j} \in P_{r,j}$ of $r \in R(j)$ within $j \in J$ is defined as:

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

Next, the number of crashes, injuries, and fatalities corresponding to each path must be assigned. The crash data source includes all the collisions that took place in the study area's network during a considered temporal period. The road and the area where the collision occurred are registered for each element. Hence, the number of crashes, fatalities, and injuries along $p_{r,j} \in P_{r,j}$ of $r \in R(j)$ within, $j \in J$ can be defined as the sum of the crashes having the same road and the jurisdiction attributes. Formally, let:

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

Then, the number of crashes on path $p_{r,j} \in P_{r,j}$ of $r \in R(j)$ within $j \in J$ during T is defined as

$$n_{r,j} = |N(r,j)| \tag{4}$$

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

$$m_{r,j} = |\mathrm{M}(r,j)| \tag{5}$$

The number of injuries on path $p_{r,j} \in P_{r,j}$ of $r \in R(j)$ within $j \in J$ is defined as:

$$i_{r,j} = |I(r,j)| \tag{6}$$

Once the road crash for each path is assigned, the modal value of the nature of the crashes that occurred has been identified (e.g., head-on collision, pedestrian impact). This is to have an overview of the most frequently occurring type of crash in each segment.

2.2.2. Step 2—Safety Indicators Computation and Road Network Ranking

Once the data are assigned to the road network, three crash-relevant indicators based on European [39] and national recommendations [26] are used in this research to be able to focus on three different aspects of the crash event: Accident Rate (AR), Injury Rate (IR), and the Adjusted Accident Cost Rate Index (AACRI).

The AR represents the number of road crashes per million vehicles per km travelled; the IR represents the number of injuries per million vehicles per km travelled; and the AACRI represents the ratio between the social costs (sum of a standardised cost assigned to the crash, to each injured and each death) at a given site over a specified period and the segment length per the related traffic volume (expressed in veh*km travelled). As Bonera et al. [6,22] proposed, the safety performance evaluation for each road path in terms of cost provides a first evaluation of how much is paid for unsafe roads and, therefore, a criterion to prioritise interventions. For this reason, it is considered as the primary index in the present study.

The three indexes can be computed as follows. Let:

- α, β and γ be the coefficients for estimating the unitary social costs associated with a road crash, a fatality, and an injury, respectively.
- f be the number of days in the considered temporal period T.
- $c_{r,j}$ be the unitary social cost.

The AR can be determined for each road path $p_{r,j} \in P_{r,j}$ of the network as follows:

$$AR_{r,j} = \frac{10^6 \cdot n_{r,j}}{f \cdot l_{r,j} \cdot v_{r,j}} \left[\frac{\text{Crashes}}{\text{milveh} * \text{km}}\right] \tag{7}$$

The IR can be determined for each *i*-th road segment of the network:

$$IR_{r,j} = \frac{10^6 \cdot i_{r,j}}{f \cdot l_{r,j} \cdot v_{r,j}} [\frac{\text{Injuries}}{\text{milveh} * \text{km}}] \tag{8}$$

The social cost can be determined:

$$c_{r,j} = \alpha \cdot n_{r,j} + \beta \cdot m_{r,j} + \gamma \cdot i_{\ r,j} \ [EUR] \qquad \forall r \in R, \quad \forall j \in J \tag{9}$$

The AACRI can be determined for each road path $p_{r,j} \in P_{r,j}$ of the network as follows:

$$AACRI_{r,j} = \frac{10^6 \cdot c_{r,j}}{f * l_{r,j} * v_{r,j}} [\frac{EUR}{\text{milveh} * \text{kmveh} * \text{km}}] \qquad \forall r \in R, \quad \forall j \in J \tag{10}$$

Once the three safety indicators are computed for each road path, they can be ranked according to the distribution of quartiles [6,22,23]. The lower, middle, and upper quartiles are used to set the thresholds (Q1 = 25%, Q2 = 50%, and Q3 = 75%, respectively), and the interquartile range (IQR) of the distribution of the ordered indicators is also introduced to help identify the more relevant segments. The hazard level ranges for each indicator are as follows: (min.) Q1 very low hazard; Q1–Q2 low hazard; Q2–Q3 medium hazard; Q3–Q4 high hazard; Q3 (max) very high hazard. The use of a five-level scale is adopted according to the European Directive (EU) 1936/2019 [19,23,40]. The goal is to offer direction to Administrations, PTCs, and practitioners on how to prioritize risk mitigation actions throughout different parts of the transit network, using established tools. Moreover, this choice is influenced by the widespread use of four or five-level scales to classify, e.g., the risk of bus crashes [41,42], the risk of fare evasion in buses [43]. Notably, individuals are not constrained to conform to preceding ranges, which can be formulated in various ways, to enhance their acceptability.

Table 1 summarises the ranking hereby presented. Next, the resulting ranking is mapped through GIS software and maps are produced. These results are available to relevant road safety authorities and will be used to provide a clearer overview of the overall safety performance of the road network of interest.

Table 1. Hazard level ranking scale.

Hazard Level		Ranges Values	
		Lower Limit	Upper Limit
5	Very high	(Q1 − 1.5 IQR) > 0	Q1
4	High	Q1	Q2
3	Medium	Q2	Q3
2	Low	Q3	(Q3 + 1.5 IQR) > 0
1	Very low	(Q3 + 1.5 IQR) > 0	MAX

2.2.3. Step 3—Georeferencing of Road Crashes Based on Kilometre Marker

Step 3 addresses the unresolved issue of accurately identifying blackspots. The quality and availability of location crash data remain a challenge in many contexts [28–30]. This limitation poses challenges to the localisation of crashes, which is partially addressed in Bonera et al. [6,22]. Specifically, an unresolved aspect relates to the accurate identification of blackspots, which is necessary to identify the most critical locations and properly target appropriate interventions. The kilometre marker data, shown to be a highly present data, are a useful data source for non-urban roads. These data are more accessible for law enforcement to recognise and identify than latitude and longitude data, which may be incorrectly recorded due to inexperience with digital tools or the inherent location error of GPS-reliant instruments, especially in contexts with reduced or disturbed satellite coverage. The localisation of crashes by latitude and longitude could significantly impact the reliability of blackspots identified through this method. The kilometre marker's unique position on the road enables greater accuracy in determining crash locations. Therefore, given the location of a few kilometric markers, with the use of GIS tools, and particularly the geoprocessing tool *points along geometry*, it is possible to reconstruct the position of the missing markers digitally, create a digital sequence of hectometres, and then proceed to associate the crashes with the kilometres and hectometres markers using the GIS geoprocessing tool *join attributes table* with a *join one to many*. This procedure is an operation that takes those elements of the father that have given rise to the sons, beginning from a father shapefile (position of kilometre markers) and a son shapefile (position of car crashes) of the same geometric type and populates these elements with the information in the son's attributes table, creating for each element of the father as many copies as there are sons that derive from it.

The positioning in a linear reference system (suburban road) of a geographical point (kilometre marker) tends to be difficult to translate, due to the length distortions that accumulate along the linear representation [44]. To reduce the accumulation of the described error, the path has to be subdivided into shorter segments using a higher number of real kilometre markers as a reference. In addition, to overcome the difference between the length of the virtual path and the actual length indicated by the real kilometre markers, the following proportion was used to find the correct distance of the virtual kilometre markers.

Let:

- L_{rkm}, be the real kilometre marker path.
- L_{hkm}, be the hypothetical kilometre marker path.
- L_{vkm}, be the virtual kilometre marker path.
- k be the ratio between the real and the virtual step.
- n be the fixed spacing to be determined due to each precision need.

$$n \ : L_{dkm} = k \ : L_{hkm} \ [m] \tag{11}$$

After the shapefile containing the virtual kilometre markers is created, one of the fields in the attributes table must report the actual value of the distance indicated by the kilometre markers. Once the unit of measurement has been transformed from metres to kilometres. The formula used is as follows:

$$L_{dkm} = \frac{k \cdot L_{vkm}}{1000} \ [m] \tag{12}$$

This resulted in a succession of virtual kilometres markers with a maximum error of around 100–150 m in mountain segments, and a minimum error of around 20–30 m in lowland segments.

The outcome is a dynamic map in a GIS environment that enables the analysis of crashes on the route under investigation.

2.2.4. Step 4—Road Characteristics Collection for Speed Processing

Steps 4 and 5 apply the operating speed model defined by Martinelli et al. [37,38]. This model is a straightforward and accurate model for estimating the operating speed of a road due to its model consistency and the limited number of data to be surveyed.

Determining both the operating and legal speeds is essential to distinguish between the intended road design and the speed indications provided to drivers. Various factors need to be recorded for each road path, including the legal speed limit, roadside length, number of accesses, overtaking restrictions, road curvature, flow of free-flowing vehicles, presence of roadside features, visibility, and surrounding terrain. The proposed model requires the road to be divided using fixed segmentation criteria. If updated road photos are available online, relevant data can be swiftly collected during an off-site visit, saving time and effort.

2.2.5. Step 5—Operating Speed Model Application

The operating speed (denoted as V'_{85}) was predicted applying an existing multiple regression model fitted to data collected in the province of Brescia in different road categories (primary and secondary) and territory environments (hills, plains, and mountains) [37,38]. Among the possible models, this model was selected because of its overall significance, which proved to be better in terms of the analysis of the residuals and of the readability of the result regarding the interpretation of the significance of the regression coefficients.

The equation for estimating the operating speed for the non-urban roads is as follows. Specifically, let:

- $L_{b,sx}$ be the width of the left side of the platform.
- A_{lat} be the number of lateral accesses.
- S_{imp} be the percentage of impeded overrun.
- K_m be the mean curvature.
- *(A/Q)* be the percentage of free-flowing cars about the total capacity handled.
- B_{pav} be the presence of the paved right platform.
- $S_{mz,pv}$ be the visibility of the central strip.
- T_m be the presence of surrounding mountainous terrain.
- N_C be the number of lanes.
- $V_{s,mar}$ be the visibility of the edge horizontal markings.

As a result:

$$\begin{aligned} V'_{85} = 69.06 + 2.25\ L_{b,sin} - 1.45\ A_{lat} - 1.45\ S_{imp} - 1491.22\ K_m + 0.22\ (A/Q) \\ +1.54\ B_{pav} + 5.06\ S_{mz,pv} - 7.05\ T_m + 11.63\ N_C - 8.17\ V_{s,mar} \end{aligned} \quad (13)$$

Details on the collection and calculation of each parameter are reported in Martinelli et al. [37,38]. Note that one does not have to obey the previous equation in the calculation of the operating speed; other regressions can be used to obtain these data and improve the acceptability of the overall methodology. Equation (11) is computed for each path.

The result is a map in a GIS environment reporting operating and legal speed data, and their difference for each path. This representation allows for easy identification of areas where the difference is most significant, whether positively (operating speed above legal speed) or negatively (operating speed below legal speed).

2.3. III—Proposal Stage

The third Stage consists of two steps (refer to the green section of Figure 1). The first step involves identifying high-hazard roads, crash blackspots (i.e., singular points with a high concentration of crashes, injuries, and/or deaths), and crash hotspots (i.e., concentrations of crash blackspots that occurred in a similar road environment over a wide area). The second step proposes measures for critical paths based on road environment typologies. It utilises a recommended set of effective practices for reducing crashes that consider the available implementation time.

2.3.1. Step 6—Critical Road Paths and Blackspot Identification

Step 6 proposes measures for critical paths based on road environment typologies, employing a recommended set of effective practices to minimise the number and mortality of collisions, considering the time available for implementation.

Therefore, Step 6 first selects road paths classified as "high" or "very high" hazards (according to AR, IR, and AACRI of Step 2) that require prioritised efforts by traffic authorities to improve safety. Next, it identifies crash blackspots according to historical crash concentrations. Each blackspot is examined and classified according to the following road environment typologies drawing from [45,46] relevant data from the official Italian road crash protocol (e.g., nature of the crash, road characteristics, location of the crash) and potential land uses. These typologies are: (i) mountain and hill roads; (ii) urban roads; (iii) curves; (iv) intersections; (v) long straight or monotonous roads; (vi) acceleration lane entry points; and (vii) roads linked to industrial/commercial/gas station activities. Additional typologies may be identified based on local environmental characteristics. An overview sheet with relevant pictures and maps to offer an extensive overview of the identified environment for each typology is made.

The final phase of Step 6 involves clustering the road network into crash hotspots, based on the geographic and thematic concentration of crash blackspots that occurred in a similar road environment over a wide area. The crash hotspots serve analytical and descriptive functions and enable network clustering into functional lots for immediate implementation or future design. The outcome includes maps of high-hazard roads, crash environment typologies, blackspots, and crash hotspots.

The operating speed data are considered relevant for identifying the crash causes and action proposal (Step 7), but not for identifying critical road paths due to its non-linear relationship with the safety indicators identified.

2.3.2. Step 7—Action Proposal

In Step 7, an abacus of measures (Table 2) is presented to assist decision-makers in choosing those feasible and pertinent for the case at hand. These measures have proven effective in reducing the frequency and/or severity of crashes. The abacus derived from the literature and international case studies is a valuable tool for decision-makers to address the issues that emerged from the previous analytic steps. It includes information regarding the speed of implementation and road environments in which a given measure is recommended. To identify the most appropriate measures to be implemented, the output of the safety indicators, knowledge of legal and operating speeds, and the identification of crash blackspots and their classification according to road environment constitute crucial information. For a more comprehensive set of measures, see Elvik [46] and Turner et al. [45].

Table 2. Abacus of measures.

Measure [Source]	Road Environment Application Suggested	Time of Implementation	Description
Central rumble strip realisation [45,47]	Mountain and hill road/Curve/Long straight and/or monotonous roads	Very fast	Mid-road rumble strips are a safety feature that vibrates the vehicle and emits an audible rumble to warn inattentive drivers of the potential danger of crossing the mid-road strip.
Lateral rumble strip realisation [45,47]	Mountain and hill road/Curve/Long straight and/or monotonous roads	Very fast	Roadside rumble strips are a safety feature that vibrates the vehicle and emits an audible rumble to warn inattentive drivers of the potential danger of running off the road.
Speed control cameras installation [45,48,49]	Curve/Long straight and/or monotonous roads	Fast	A speed camera is placed on the road to photograph cars travelling faster than the speed limit, aiming to fine offenders and reduce vehicle speed.
Pedestrian crossing lighting improvement [35,44–46,50–52]	Urban road	Fast	Pedestrian crossing lighting is a safety feature that increases the visibility of pedestrian crossings at night.
Placing of impact absorber on guard rails posts [53–56]	Mountain and hill road/Curve	Fast	An impact absorber is a protective device placed on the guardrail posts to minimise injuries with limited implementation costs.
Addition of sub-rail on guard rails for motorcycle safety (MPS) [46,54–56]	Mountain and hill road/Curve	Medium	An additional subrail is fitted under the guardrail to dampen or prevent direct driver impact with the guardrail post and prevent the driver from slipping under the guardrail.

Table 2. *Cont.*

Measure [Source]	Road Environment Application Suggested	Time of Implementation	Description
Pedestrian fencing realisation [46,52]	Urban road	Medium	Pedestrian fencing is implemented to prevent pedestrians from crossing the road at unsafe locations and to direct them to safe crossings.
Raised pedestrian crossing realisation [45,57,58]	Urban road	Medium	Pedestrian crossings are raised to improve pedestrian visibility and reduce vehicles speed.
Left turn reduction [45,59]	Urban road/Intersection/Roads linked to industrial/commercial/gas station activities	Medium	Reducing left turns aims to reduce the number of vehicles crossing the road and redirect them to safer turning points through various measures (signs, barriers, etc.).
Traffic calming measures in urban environments [45,46]	Urban road	Medium	Implementing traffic calming measures in the urban environment aims to reduce vehicles average speed and reduce the number and severity of crashes (especially for vulnerable road users).
Roundabout realisation [45,46,60]	Intersection/Roads linked to industrial/commercial/gas station activities/Urban road	Slow	Roundabouts are designed to reduce potential conflicts between vehicles while reducing vehicle speed and increasing safety.
Adjustment of the extension of the acceleration lane [61–63]	Acceleration lane entry	Very slow	Adjusting the length of acceleration lanes is intended to make it easier for vehicles to enter higher-ranked roads from lower-ranked roads, making their entry safer.
Subpasses at railway-level crossings realisation [64,65]	Intersection	Very slow	Replacing railway level crossings with subpasses is intended to reduce potential conflicts between rail and vehicle traffic by making railway crossings safer and smoother as a result.
Emergency lanes or emergency lay-by realisation [46,66]	Mountain and hill road/Long straight and/or monotonous roads	Very slow	The purpose of lay-bys is to allow damaged or distressed vehicles to stop safely without obstructing normal traffic flow and to facilitate the arrival of emergency vehicles.
Grade separation at intersections realisation [45,46]	Intersection	Very slow	The construction of grade separation at intersections is intended to reduce potential vehicular conflicts on highways and primary roads by ensuring greater safety and smoother traffic flow.

3. Results

3.1. The Context

The "Via Olimpica" is a more than 208-km road track formed by the state roads SS 36 "dello Spluga" and SS 38 "dello Stelvio" that connects the regional capital of Milan with the Valtellina skiing resorts, which will be the venue for the 2026 Milano–Cortina Winter Olympic Games. Our research also included the 72-km stretch of road that runs from the Fuentes Crossing to the Spluga Pass (see Figure 2).

The roads examined (except for short stretches) are mainly non-urban. From Milan to Verano Brianza (MB), it consists of a dual carriageway with a three-lane road for each direction (ca. 18 km); from Verano Brianza to Morbegno it consists of a dual carriageway and double-lane road for each direction (ca. 76 km); and from Morbegno to the ski resorts, it consists of a single carriageway and single-lane road for each direction (ca. 114 km). On this road were registered 3153 road crashes, 55 deaths, and 5046 injuries over 7 years between 2015 and 2021.

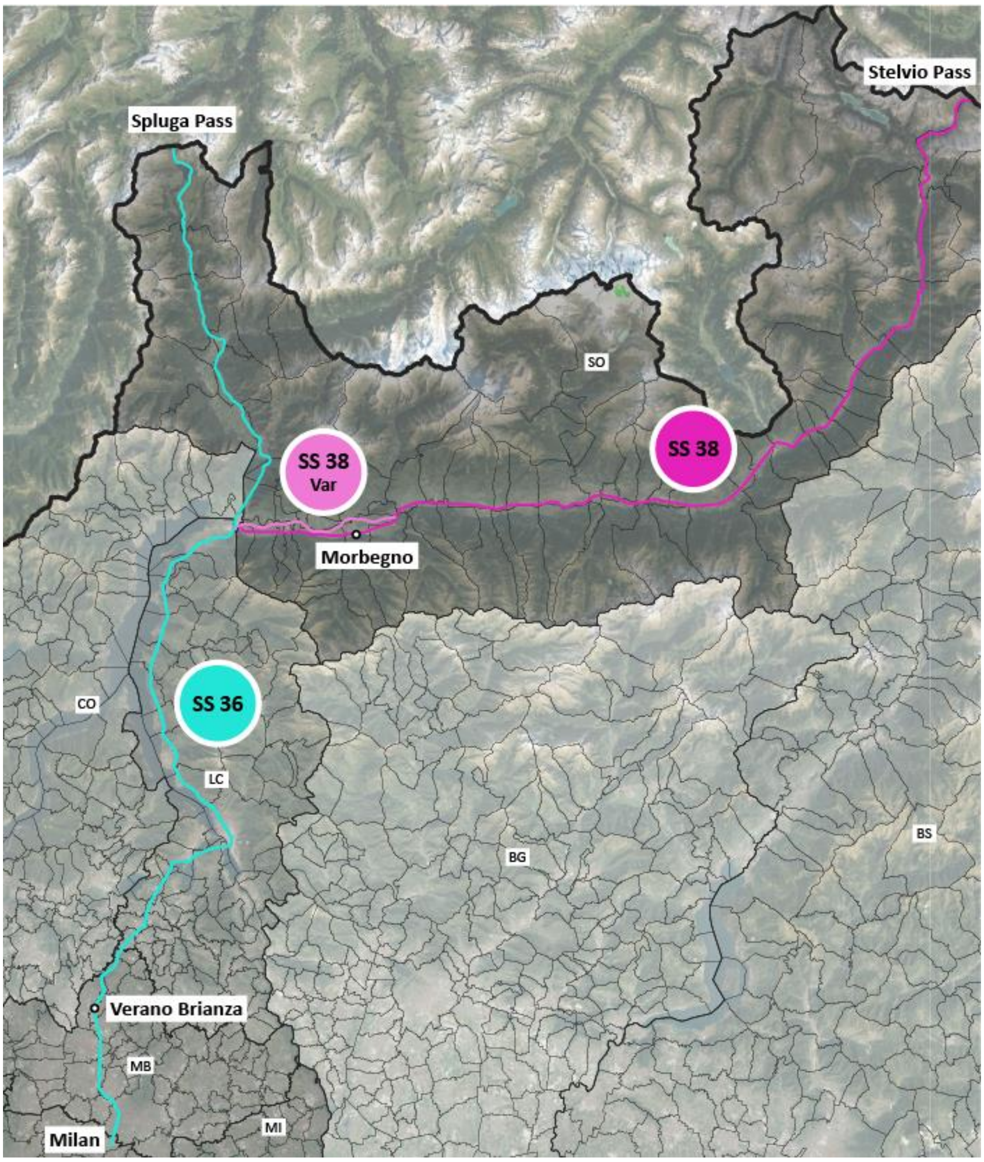


Figure 2. "Via Olimpica" road, composed of the state roads SS 36, SS 38, and SS 38 Var.

The road runs through some of the most heavily inhabited and urbanised areas of Lombardy, as well as mountainous areas with tortuous roads. The Olympic event of 2026 prompted the Lombardy Region to assess the road's safety status to identify the measures that ought to be implemented to improve its safety.

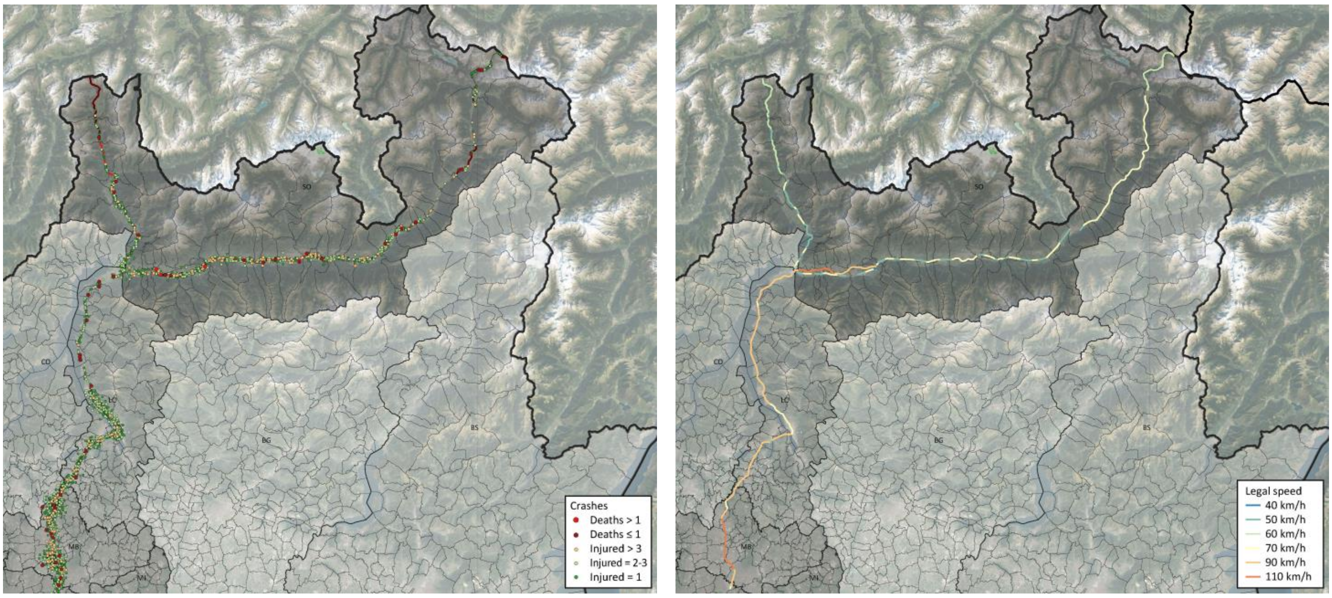
To summarise the "Via Olimpica" is a road characterised by various environments and conditions of the road infrastructure that will see a considerable increase in traffic when the world event takes place in a very short time interval. Therefore, a rapid analysis and proposal of improvement measures were required. Thus, this experiment provided a good case study from which lessons can be learned for other future situations in the European context.

3.2. Experimental Setup

According to Stage I (refer to Figure 1 for help identify titling), (a) the basemap data were retrieved in shapefile format from the open-access regional topographic database.

They included the administrative boundaries of the whole region, provinces, and municipalities. (b) The regional Directorate General provided the shapefile containing the traffic data and the road network graph. Each road segment in the graph was assigned a road name, road type, and AADT. Finally, PoliS-Lombardia (i.e., the Regional Institute for Policy Support) provided (c) crash data that occurred on the road track under analysis between 2015 and 2021. The data included all the main elements of the national statistical road crash template and were supplied in spreadsheet format. In particular it contained: crash data and location (i.e., province and municipality codes, road name or code), road type, location attributes (e.g., segment and/or intersection type, pavement type), and number of people involved [67]. Noteworthy, only 41 (1.3%) crash records failed the kilometre marker reference after the data integration. It was possible to integrate the missing kilometre marker reference for a total of 113 (3.6%) crash records. A total of 3153 crashes and 138 road segments were included in the analysis, after data pre-processing.

An off-site investigation was performed to reconstruct kilometre marker position data. The missing kilometre and hectometre data were digitally recreated in a GIS context. Finally, the (d) data required to compute the operating speed was acquired through an off-site investigation of the road for each fixed-length segment. Due to the different requirements imposed by the operating speed model (e.g., accurate calculation of road curvature), the road network has been divided into fixed-length segments of 600 m rather than by administrative boundaries. This different subdivision is more accurate than the administrative subdivision used for the safety indicators, ensuring comparability between the two. Figure 3 shows the results of both (Figure 3a) the crash geolocation process, and (Figure 3b) the legal speed data mapping.



(a) (b)

Figure 3. (**a**) Crash concentration by number and severity assigned to kilometre markers and (**b**) legal speed data.

3.3. Framework Development and Results

The framework was implemented according to Sections 2.1–2.3. The software QGIS was used in all the Steps involving data gathering and was the final output of almost all steps involving data representation in maps. Other GIS software could be used to perform both data gathering and data representation and improve acceptability of the model.

Refer to Figure 1 to help identify step titling in the present chapter.

Specifically, Stage II steps 1.1, 2.5, 3.6, 4.7, 4.8, 5.10 and Stage III steps 6.11 and, 6.12 were performed using the QGIS tool respectfully to: (i) represent the existing geographical basemap data and traffic data; (ii) represent the road network ranking according to the safety indicators computed; (iii) collect kilometre marker data and digitally reconstruct the position of missing markers as well as the sequence of hectometres; consequently, locate the crashes at the identified hectometre; (iv) collect road characteristics for 600-m segments for operating speed calculation; (v) collect road legal speed for 600-m segments; (vi) represent the difference between operating and legal speed; (vii) represent the critical road segments for priority intervention; (viii) represent the crash blackspots and hotspots and classify the firsts per typical road environment.

Stage II Steps 1.2, 1.3, 2.4, 2.5, and 5.9 were performed in MS Excel as formula computation was more straightforward, specifically to: (i) compute and (ii) assign traffic volume (Equations (1) and (3)) and number of road crashes, injuries, and deaths to each segment (Equations (4)–(6)); (iii) compute and (iv) assign the safety indicators (Equations (7), (8) and (10)) to each segment and rank accordingly to the percentile ranking scale chosen; (v) compute and (vi) assign the operating speed to each 600-m segment (Equation (13)). Other calculation software could be used to perform calculation and improve acceptability of the model. Moreover, Step 5.9 results were validated using a traffic laser scanner instrument to measure speed in relevant sections of the road track to test the results of the model. It was found a mean difference between the model and the reality of 6.9 km/h.

The procedures defined in step 6.12 were explicitly performed through:

(i) An analysis of the concentrations of crashes, injuries, and deaths in the critical road sections that lead to the identification of the blackspots.
(ii) An analysis of the data of these crashes together with off-site and/or on-site inspections of all the blackspots.
(iii) The classification of all the blackspots identified in one of the seven different typologies of road environments.

Step 7.13 was performed by realising and exemplifying the sheet for each typology of road environment identified in the investigated context and suggesting measures for each environment using the recommended abacus.

Tables 3–7 summarise tabularly the results obtained regarding Accident, injury and Adjusted Accident Cost Rate Index, difference between operating and legal speed and blackspot typologies.

Table 3. Accident rate index—Municipal level.

Hazard Level	Number of Road Segments	Percentage
5—Very high	5	3.76%
4—High	21	15.79%
3—Medium	28	21.05%
2—Low	37	27.82%
1—Very low	42	31.58%

Table 4. Injury rate index—Municipal level.

Hazard Level	Number of Road Segments	Percentage
5—Very high	4	3.01%
4—High	21	15.79%
3—Medium	27	20.30%
2—Low	41	30.82%
1—Very low	40	30.07%

Table 5. Adjusted Accident Cost Rate index—Municipal level.

Hazard Level	Number of Road Segments	Percentage
5—Very high	5	3.76%
4—High	21	15.79%
3—Medium	28	21.05%
2—Low	37	27.82%
1—Very low	42	31.58%

Table 6. Difference between operating and legal speed.

Difference between Operating And Legal Speed	Number of Road Segments	Percentage
−40% ÷ −30%	2	0.43%
−30% ÷ −15%	5	1.09%
−15% ÷ −5%	13	2.84%
−5% ÷ +5%	56	12.23%
+5% ÷ +15%	110	24.02%
+15% ÷ +30%	224	48.91%
+30% ÷ +60%	48	10.48%

Table 7. Blackspot typologies.

Blackspot Typologies	Number of Blackspots	Percentage
Urban road	5	8.33%
Curve	9	15.00%
Intersection	17	28.33%
Roads linked to industrial/commercial/gas station activities	19	31.66%
Acceleration lane entry	7	11.66%
Mountain and hill road	3	5.00%
Long straight and/or monotonous roads	0	0.00%

To summarise results showed that:

(i) A total of 24% of the road segments need priority intervention (Figure 4a–d,f–i).

(ii) In total, 83.4% of the road segments have a difference between operating speed and legal speed from 5 to more than 60 km/h (Figure 4k).

(iii) In total, 4.3% of the road segments have a difference between operating speed and legal speed from −5 to less than −40 km/h (Figure 4k).

(iv) A total of 60 blackspots were identified (Figure 4l).

(v) A total of 8 crash hotspots were identified (Figure 4m).

Figure 4n is an example of a part of an overview sheet that has been implemented. In the exemplary blackspot identified in Tirano (Sondrio), it was recommended to raise all pedestrian crossings, add bush barriers to prevent unregulated pedestrian crossings in some parts of the urban track, and implement traffic calming measures to reduce speed in the urban environment (which was discovered to be one of the main problems in this track section).

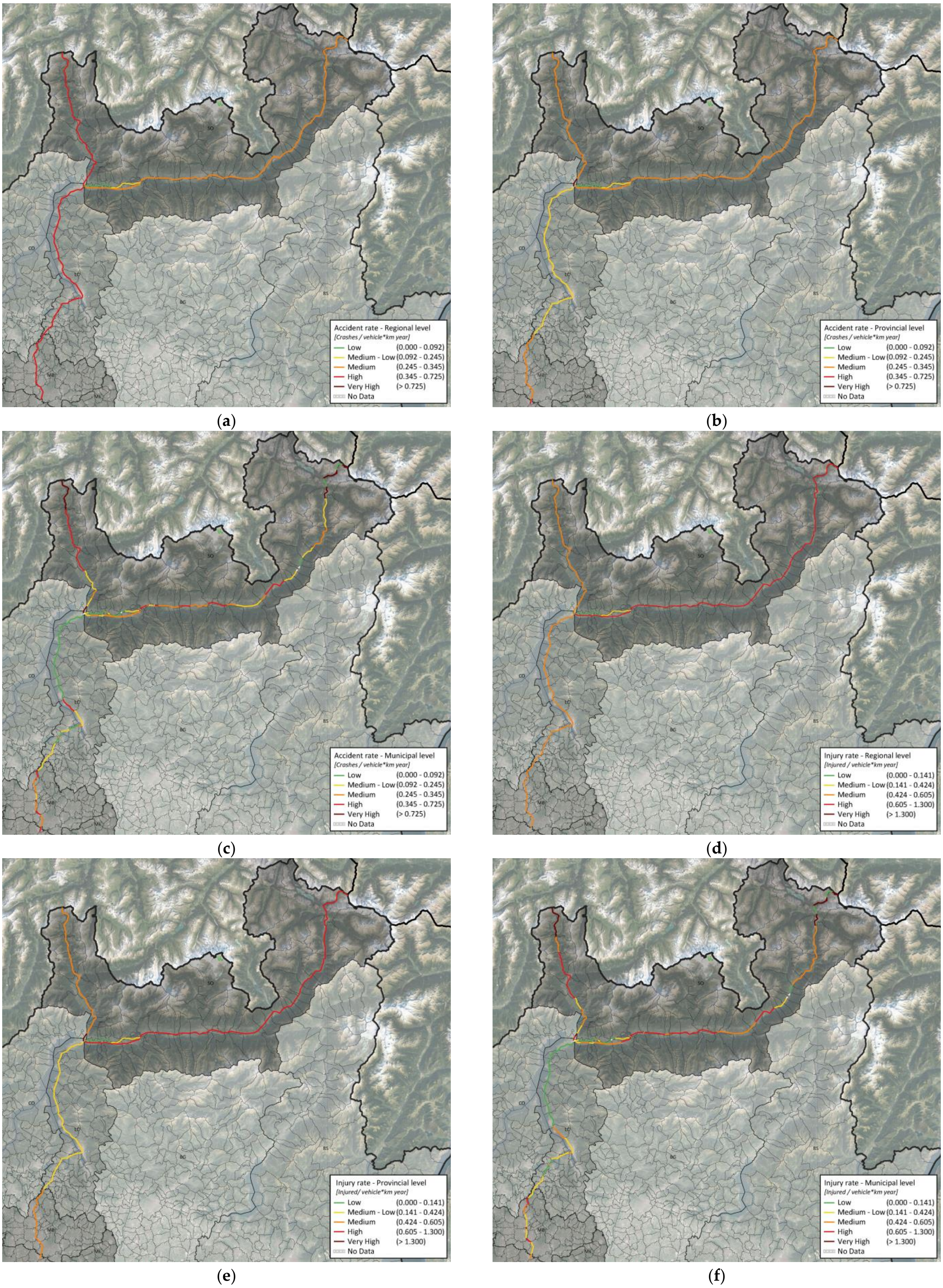
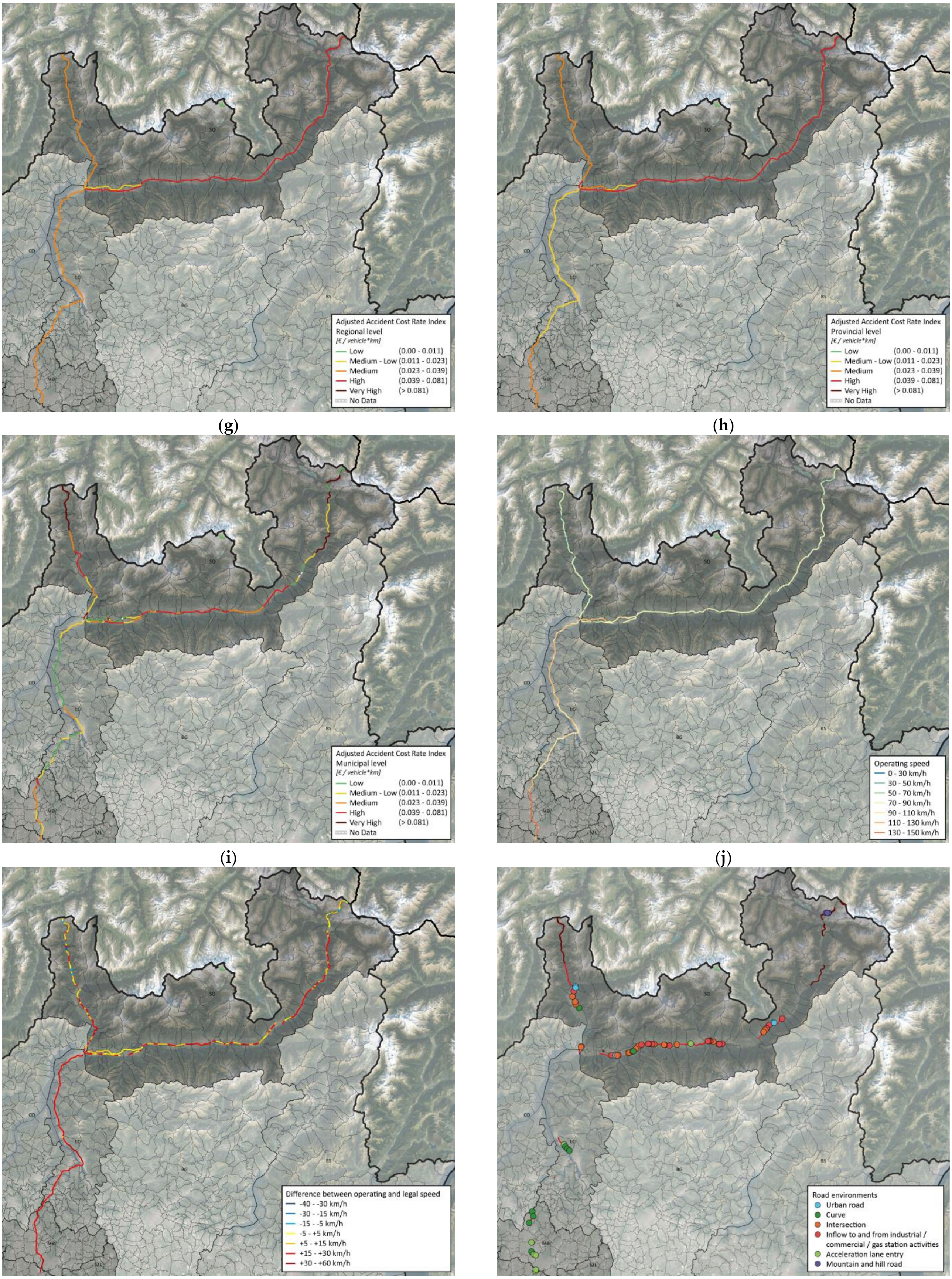
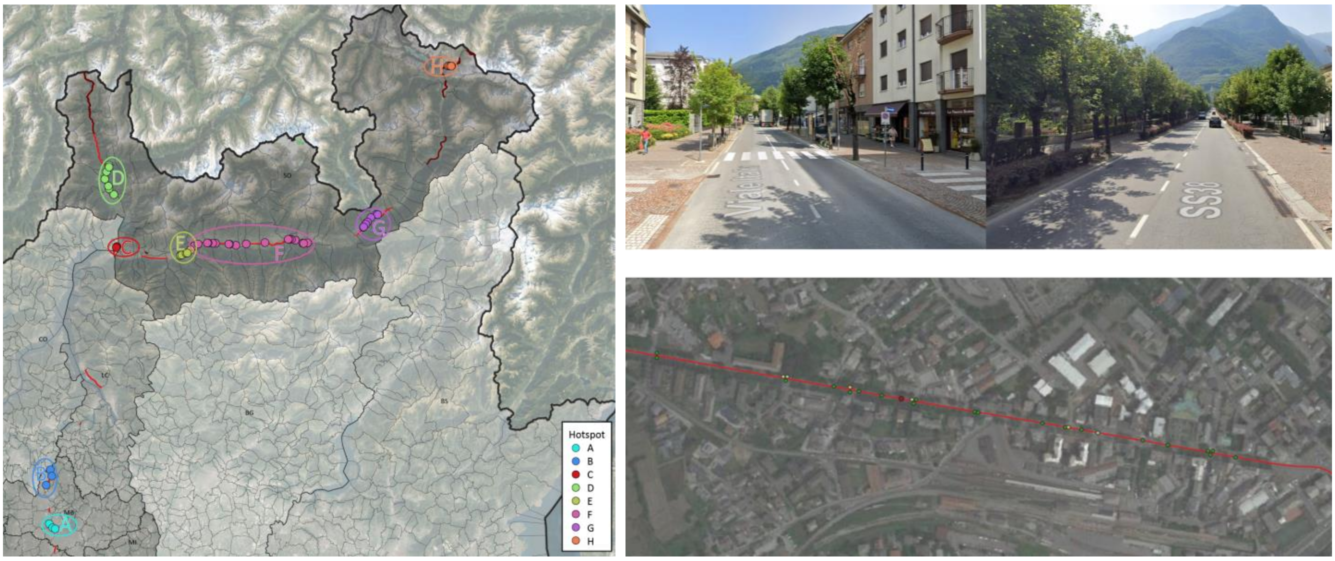


Figure 4. *Cont.*



(**g**) (**h**)
(**i**) (**j**)
(**k**) (**l**)

Figure 4. *Cont.*



(**m**) (**n**)

Figure 4. (**a**) Crash rate—Regional level; (**b**) Crash rate—Provincial level; (**c**) Crash rate—Municipal level; (**d**) Injury rate—Regional level; (**e**) Injury rate—Provincial level; (**f**) Injury rate—Municipal level; (**g**) Adjusted Accident Cost Rate index—Regional level; (**h**) Adjusted Accident Cost Rate index—Provincial level; (**i**) Adjusted Accident Cost Rate index—Municipal level; (**j**) Operating speed; (**k**) difference between operating and legal speed; (**l**) blackspots classification per typology of road environment; (**m**) crash hotspots; and (**n**) example of a road environment (Tirano)—Urban Road.

4. Discussion

Tables 3–7 and Figure 4 provide interesting insight regarding the safety status of SS 36 and SS 38.

A quarter of the road segments analysed need priority intervention, and an analysis of where these road segments are located shows that they are mostly concentrated along the SS 38, with only a small part near the cities of Monza and Milan along the SS 36. Therefore, also the blackspots identified are mostly concentrated along the SS 38. The typologies of blackspots identified herein are mostly classified within the of “intersection” and “Roads linked to industrial/commercial/gas station activities” typologies indicating a relevant issue in terms of unresolved trajectories conflicts.

The difference between the operating speed and the legal speed shows a mismatch on almost all the road segments analysed, with the segments of the SS 36 between Milan and the Valtellina valley identified as the most critical, with a difference of between 15 km/h and 60 km/h. This is probably because the road is a dual carriageway with two lanes in each direction, which encourages higher speeds, although the road geometry does not safely support such higher speeds, as can be observed in the ‘curve’ blackspots near Milan and Monza, where most off-road accidents occurred.

In order to have a feedback on the relevance of the presented framework a similar road safety study performed by ACI [68] on the same road using the iRAP-Star Rating methodology [69] has been analysed. Although these results are quite similar, they show that some portion of the road resulted safer than the results of our method. There are two main reasons for this.

First, the methodology of ACI defines the safety of each section analysed based on an overall risk factor. It was calculated as the sum of individual risk factors according to the probability and severity of each possible crash event. They are defined based on road characteristics, traffic flow, operating speed, and the possibility of invasion of the opposite lane, without considering historical crash data and using a scale with fixed (pre-defined) thresholds not built on specific contextual data (and therefore more country-comparative-oriented than contextual). Conversely, our framework considers the actual distribution of the number of crashes, deaths, and injuries on the path at hand as a fundamental element. Moreover, it identifies blackspots and grade the hazard scale according to the actual historical number of crashes on the road track considered.

Second, the intervention measures identified by ACI resulted from the automatic formulation of proposals provided with ViDA online software. It does not assess their real application on the specific road track as it does not consider the specific road environments, the dynamics of the crashes, nor their location on the road track. Conversely, our framework allows us to define a more refined context-based set of actions, which will be further evaluated for final implementation. Indeed, it begins with the identification of blackspots, their classification into road environments, and the creation of overview sheets for each road environment identified in the road context.

Key findings from the application of the present framework on the present case study, also compared with other studies performed on the same context, underscore significant insights, including the identification of road segments necessitating priority intervention, disparities between operating and legal speeds across segments, and the delineation of blackspots and crash hotspots. These findings emphasize the imperative for proactive measures aimed at mitigating road-related risks and enhancing overall safety within the transit network.

Overall, the framework's application demonstrates its efficacy in analysing and addressing safety concerns within the context of car crashes, offering valuable guidance for policymakers, transit authorities, and practitioners alike. Further research and refinement of the model, alongside ongoing monitoring and evaluation are warranted to continually improve road safety outcomes.

5. Conclusions

Despite advancements over the past decades, road safety remains an important social and health issue that needs to be addressed. Large-scale sporting and/or cultural events with an (inter)national profile and influence such as mega-events, pose increased risks and social costs for both locals and tourists due to concentrated traffic over a short period of time [14–16,36]. Local authorities face a significant challenge in addressing these negative externalities and achieving the crash international reduction targets [1,7,8] especially given the limited time for screening and implementation. Therefore, it is desirable to establish easily applicable methodologies for practitioners who may lack the expertise or skills required to execute nuanced and tricky models. This will assist decision-makers in identifying high-hazard roads and selecting feasible and relevant measures to prevent road crashes, fatalities, and injuries in an increased-risk scenario.

Although the present literature has yet to establish through extensive studies a strong cause-effect relationship between the hosting of mega-events and the increase in traffic and the number of vehicular crashes, some indications to this extent have emerged. This study contributes to the literature by integrating existing techniques and tools in an operating framework to improve road safety in scenarios with limited time for screening and implementation (e.g., mega-events) targeted explicitly for addressing these overlooked risks and social costs. Specifically, it:

(i) Provides a rapid, precise, integrated, and communicable methodology to assess road safety, identify the blackspots, classify them in road typologies and suggest to decision-makers improvement actions spatially limited and whose implementation is possible with restricted time for implementation.
(ii) Proposes a novel method that uses kilometre marker data to address the need to geo-reference car crashes in a scenario with a limited time frame.
(iii) Proposes the classification of blackspots in road environments together with an abacus of actions with confirmed effectiveness in reducing the number or severity of crashes as a flexible and viable criterion in the identification of actions to improve the level of security of a road.

(iv) Proposes clustering blackspots into hotspots based on their geographic and thematic concentration of crash blackspots that happened in similar road environments over a wide area. This enables network clustering into functional lots for immediate implementation or future design.

Future research directions to be investigated will be:

(i) Establishing more thoroughly the cause-effect relationship between the hosting of mega-events and the increase in traffic and the number of vehicular crashes to better frame the urgency of these improvement measures.
(ii) Integrating the proposed abacus with the cost parameters.
(iii) Specifying the time and cost of implementation more precisely through an analysis of international case studies.

This would enable the estimation of the impacts of road safety improvements in the overall studies of the mega-event effects, as well as the estimation of implementation costs and timing, enabling the addition of an extra step to forecast the cost and timing of different intervention scenarios for one or more blackspots or crash hotspots.

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Data Availability Statement: Restrictions apply to the availability of the crash and traffic data and the availability of the road network map. Data were obtained from PoliS-Lombardia and are available from the authors with the permission of PoliS-Lombardia. Kilometre markers, legal speed, and the road characteristics used for estimating the operating speed were registered by the authors and are available from the authors.

Conflicts of Interest: The funders of the research had a role in defining the objective of the research (identify the high-hazard roads and identify possible measures to reduce the hazard), but they did not have any role in the design of the study, in the definition of the research methodologies to be used, in the analyses or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

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