Mapping Risk Factors to Build Inclusive Roads: A Systematic Diagnosis for Enhancing Vulnerable Users and Persons with Reduced Mobility Safety

Davide Maestroni[1(✉)], Giuseppe Cappelli[2], Valerio Gagliardi[3], Sofia Nardoianni[2], Pooyan Hejazi Mahabadi[1], Trigaluh Prastyana Tika[1], Neritan Caushaj[1], Francesco Bella[3], Mauro D'Apuzzo[2], and Francesco Edoardo Misso[1]

[1] BV Tech S.P.A, Via Delle Coppelle, 35, 00186 Rome, Italy
{Davide.Maestroni,Pooyan.HejaziMahabadi,trigaluhprastyana.tika,francesco.misso}@bvtech.com

[2] University of Cassino and Southern Lazio, Via G. Di Biasio 43, 03043 Cassino, Italy
{giuseppe.cappelli1,sofia.nardoianni,dapuzzo}@unicas.it

[3] Department of Civil, Computer Science and Aeronautical Technologies Engineering, Roma Tre University, Via Vito Volterra 62, 00146 Rome, Italy
{valerio.gagliardi,francesco.bella}@uniroma3.it

Abstract. Sustainable transport has been a growing focus for several decades, particularly following the Paris Agreement in 2015 and the Glasgow Climate Pact in 2021. The United Nations Sustainable Development Goal (SDG) 11 promotes accessibility, safety, energy, efficiency and use of sustainable public transport. Access to safe, reliable, and affordable transportation is fundamental for social inclusion, education, healthcare, and employment. Building on these global initiatives, this research aims to identify critical road safety risks and proposes targeted interventions to improve mobility for vulnerable road users (VRUs) and persons with reduced mobility (PRMs) in Italy. It applies principles of social sustainability in transportation to assess road safety in Rome's Nomentano-Tiburtina area through three interrelated studies. First, the accident analysis identifies high-risk "black points" by mapping accidents involving VRUs through Geographic Information System (GIS) and Kernel Density Estimation (KDE). Then, the vehicle-infrastructure interaction analysis evaluates road infrastructure risks using floating car data (FCD) to analyze driver behavior and correlates it with road accident data. Finally, the accident potential analysis assesses pedestrian accident risk by examining pedestrian flows and urban network structures, integrating configurational analysis with SpaceSyntax tools. Using FCD, multi-year accident data and pedestrian flow analysis, this research provides a comprehensive assessment of road safety risks in Nomentano-Tiburtina. The integration of the three quantitative information, allows the identification of critical areas and the development of targeted interventions. Findings offer actionable insights for policymakers and urban planners to enhance pedestrian, cyclist and vulnerable users' safety and promote sustainable mobility in urban environments.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2026
O. Gervasi et al. (Eds.): ICCSA 2025, LNCS 15898, pp. 87–104, 2026.
https://doi.org/10.1007/978-3-031-97657-5_6

Keywords: Road Safety · Kernel Density Analysis · Pedestrian Crowding

1 Introduction

In 2021, the Federal Highway Administration (FHWA) launched the Safe System Strategic Plan [1], as an approach toward zero traffic deaths. The main principle on which this plan is founded is the need to adopt a Safe System approach, aimed at ensuring no one is killed or injured on roads. It is worth mentioning that other initiatives, such as Vision Zero [2], Toward Zero Deaths: A National Strategy on Highway Safety [3], and Road to Zero [4], are all focused on reducing road accidents and are also implementing this Approach. Although there are several measures to improve safety, the Proven Safety Countermeasures promoted by FHWA aim to help ensure the five elements proposed in the Safe System Approach, with emphasis on safe road users, speeds, and roads [5–7]. The area in which these countermeasures are proposed regards speed management, roadway departure, intersections, pedestrian and cyclist infrastructures, and crosscutting.

The category of vulnerable users that is most at risk is people with reduced mobility. Among people with reduced mobility, it is possible to find old pedestrians. Jancey et al. [8] in their work highlight the importance of maintaining high levels of activity when physical and mental activity levels start to decline, and walking is one of the most common activities among the elderly. For these reasons, the authors assume that safety should be prioritized to promote safe walking activities in urban areas, thereby enhancing the safety of Vulnerable Road Users.

In a study conducted in the city of Itajubá, Brazil, Lima e Machado [9] evaluate the accessibility of individuals with reduced mobility with a quantitative and a qualitative methodology, by introducing an accessibility index, based on the judgements of participants. They found that the width, the ground surface, and the slope of the sidewalk have a strong impact on the accessibility of these users.

In agreement with these results, Gaglione et al. [10] found that factors that limit accessibility for the elderly are the slope of sidewalks (especially when this value exceeds 5%), poor street lighting, and the volume of vehicular traffic.

Kwon and Akar [11] study the interaction between the use of public transit and disabled people in California. They found that individuals with reduced mobility use transit services more frequently than not disabled persons, and this phenomenon is higher when individuals live in walkable and accessible neighborhoods. Non-worker disabled, on the contrary, are less prone to use transit. They also found that, in general, a high level of walkability is strongly related to a high level of transit usage by disabled individuals.

To make safer and more accessible roads for vulnerable users and individuals with reduced mobility, this paper presents an innovative and hybrid methodology (as described in Sect. 2) that integrates the analysis of floating car data (FCD), road users' accidents, and pedestrian crowding models. The methodology is applied to the Nomentano-Tiburtino area in Rome, with a brief description of the case-study area provided in Sect. 3. In Sect. 4, all the results with the different methodologies applied in Sect. 2 are reported and shown. In the same Section, by combining all the outputs from the

three different analyses, critical areas are identified and ranked by using a Risk Indicator factor (Subsect. 4.4). After that, countermeasures (Subsect. 4.5) are proposed to reduce the probabilities of road accidents by modifying the crash modification factor (CMF).

2 Method

2.1 Data Description and Kernel Density Estimation (KDE)

To develop the methodology for identifying hazard levels across different sections of the road network, several types of datasets have been acquired:

- Road Accident Data (2011–2020) [12], to identify accident hotspots, which contains the main details on vulnerable user's road crashes
- FCD (2022–2023): Real-time data collected from devices installed inside vehicles, capturing valuable information such as GPS coordinates, date and time, speed, weather conditions, direction, and more. This data provides insights into driver behavior, including anomalous events like sharp braking and rapid acceleration, which we will use in our study.
- Road Accident Data (2017–2019): Extracted from the official site of 'Roma Capitale' [12], this dataset includes information on location, date and time, and type of incident. It serves as the ground truth to evaluate whether anomalous driving patterns from FCD correlate with actual crash events, helping to identify high-risk zones.

Kernel densities of these data have been estimated. KDE [13] is a non-parametric statistical technique used for smoothing data and estimating the probability density function (PDF) of a random variable (Eq. 6):

$$\mathrm{f(x)} = \frac{1}{n\mathrm{h}} \sum_{i=1}^{\mathrm{n}} K\left(\frac{x - x_i}{h}\right) \tag{6}$$

where:

f(x) is the kernel density.
n represents the number of data points (e.g., FCD or accident data).
h denotes the bandwidth, beyond which any data point is disregarded.
K(.) represents the kernel function, which can take various forms (e.g., triangular, uniform, quartic, Gaussian, etc.). In this research, the Gaussian form was used.

2.2 Accident Analysis of Events Involving VRUs

This step of the research aims to map the spatial distribution of accidents involving VRUs in Rome, focusing on the Nomentano-Tiburtina area, selected as a case-study area. The goal is to identify accident hotspots to improve road safety measures. As part of a collaboration with Roma Servizi per la Mobilità, a dataset spanning 10 years (2011–2020) was collected, containing detailed information on accident locations (coordinates in WGS 84), dates, times, types, and VRU categories (pedestrians, motorcyclists, cyclists). A Geographic Information System (GIS) and a KDE approach were applied to identify high-risk areas, or "black points." The KDE with barriers enabled the identification of

the most critical areas for VRU accidents, establishing a legend based on statistical values, such as the mean and standard deviations. An analysis of sensitivity was conducted by varying the parameter h among values of 50, 100, and 150 m, revealing that the measure of 100 m provides the most suitable results considering the characteristics of the study area. This outcome confirms findings from similar investigations conducted in urban areas in Italy, akin to the study area [14]. To develop density analysis while considering the urban nature of the study zones, surfaces were modeled using external software outside the GIS environment to create "barrier" entities for use in subsequent KDE approaches. Both building structures and barrier positions were considered to obtain an accurate and detailed representation of the road network graph of the study area (Fig. 1). The spatial distribution of incidents was analyzed using KDE, incorporating the presence of physical barriers. This approach facilitated the identification of areas with higher incident concentrations, accounting for the influence of barriers (buildings, green areas, etc.) in determining kernel density.

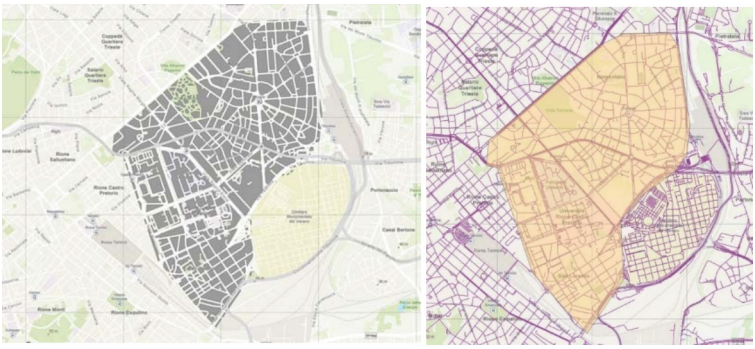

Fig. 1. Creation of a road network graph, consisting of edges and nodes within the study area and creation of barriers (in gray), corresponding to areas excluded from the KDE calculation.

In this study, given the complexity of statistical models and the absence of comprehensive data for model development, a statistical definition was chosen with some degree of arbitrariness in setting interval extremes, consistent with literature recommendations from similar studies conducted in urban environments of Italian cities [14]. Specifically, the risk classification was established as follows:

$$f(u, v) \leq \mu \tag{1}$$

$$\mu \leq f(u, v) \leq \mu + 2\sigma \tag{2}$$

$$\mu + 2\sigma \leq f(u, v) \leq \mu + 4\sigma \tag{3}$$

$$\mu + 4\sigma \leq f(u, v) \leq \mu + 6\sigma \tag{4}$$

$$f(u, v) \geq \mu + 6\sigma \tag{5}$$

where μ is the mean value of the density surface, σ is the standard deviation, and *f(u, v)* represents the density value at a generic position *(u, v)*. The final interval (class 5) was chosen/selected to identify hazardous road sites. The selection of the last interval highlights points with a very high concentration of collision events, characterized by kernel densities exceeding the mean value plus 6 standard deviations. In other words, selecting the last interval, which is highly restrictive from a statistical perspective, highlights points with significant concentrations of incidents, directing the analysis toward those sites that are highly critical in terms of VRU accidents.

2.3 KDE of Road Accidents and FCD

To identify the most dangerous intersections using FCD, KDE was applied to analyze the data. Several preprocessing steps were necessary to evaluate whether there is a correlation between anomalous FCD and incident data. These steps enabled the subsequent evaluation of the correlation between FCD and incident data.

First, KDE was applied to the data with a bandwidth (h) of 100 m to account for barriers in urban environments, on both FCD anomalies (acceleration values exceeding + 0.35g and falling below -0.45g) [15] and incident data. The final output is a georeferenced raster image, with each 10-m pixel representing road infrastructure and containing the Kernel Density value.

Next, a mask was created from the road network of the study area. This involved creating a 10-m buffer around the road network, resulting in a shapefile. The buffered shapefile was rasterized to produce a raster with a pixel size of 1 m by 1 m, assigning a value of 1 to all pixels within the buffered area to create a mask.

The mask was then applied to the KDE with barriers heatmap using the Raster Calculator, producing a refined heatmap that includes only the areas of interest within the buffered road network. Finally, the KDE of accidents was compared with FCD anomalies to assess correlation between the two datasets, using the Pearson Index.

2.4 Assessing Pedestrian Crowding Using Space Syntax

Pedestrian analysis was conducted through an integrated hybrid approach combining configurational spatial analysis techniques with predictive demand-driven models for spatial analysis techniques with predictive models of pedestrian mobility [16, 17].

The objective was to assess the accessibility of the pedestrian network, identify critical points in terms of accident risk exposure, and propose mitigation measures based on quantitative indicators.

To examine the structure of the pedestrian network, a new configurational approach was employed, combining Space Syntax analysis, a configurational method that quantifies the geometric and functional characteristics of pedestrian infrastructures, with a demand-driven pedestrian analysis.

In particular, Integration, the minimum number of steps required to reach a network node, has been taken into consideration as a key indicator.

3 Case Study

After monitoring several urban sectors of Rome, the Nomentano – Tiburtino area (see Fig. 2), which is part of Municipio II, was selected as the study area as it aligns with the future context of Pietralata for the following reasons: presence of hospitals, university buildings and of several metro stations in both areas, proximity to Roma Tiburtina Railway Station, usage for productive activities and service distribution rather than residential purposes. However, each area has its specific characteristics, such as: higher population density in Nomentana Tiburtina area compared to other areas [18], greater touristic attractiveness of Nomentana Tiburtina due to its central location. Analytical distortions arising from the presence of the Roma Termini railway station and the Verano cemetery in the Nomentana-Tiburtina area [19], as well as the forthcoming stadium in Pietralata, which is absent in the Nomentana-Tiburtina area [20].

In addition, a high incidence of accidents involving Vulnerable Road Users (VRUs), particularly pedestrians and motorcyclists, was observed, making this case study particularly suitable for testing the proposed analysis methodology.

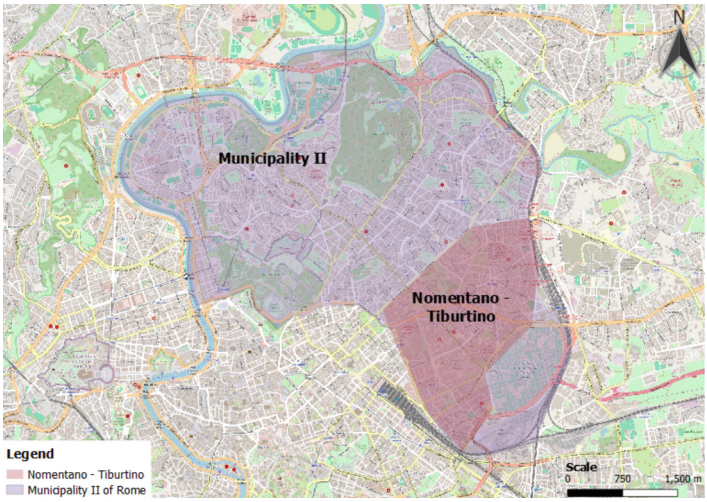

Fig. 2. Case study framework

4 Results

4.1 Road Accidents Involving VRUs - Identification of Black Points

The identification of black points, defined as critical areas with a high concentration of road accidents involving Vulnerable Road Users (VRUs), was carried out using a Kernel Density Estimation (KDE) analysis, following the methodology described in Sect. 2.2. This approach enabled the detection of spatial clusters where accident density is significantly elevated. In particular, accident classes 4 and 5, as detailed in Sect. 2.2, revealed

an anomalous concentration of incidents involving VRUs. Based on this analysis, five black points were identified, characterized by heterogeneous features: two located in urban squares and three at road intersections.

More specifically, based on the analysis of the KDE with barriers, the following sites have emerged as high-risk points (Fig. 3):

- Piazzale del Verano.
- Piazza delle Provincie.
- Viale Regina Elena and Viale dell'Università.
- Via Giovanni B. Morgagni and Viale Regina Margherita.
- Viale Pretoriano and Viale Piero Gobetti



Fig. 3. Output of KDE with barriers - Identification of black-points (in orange).

4.2 Correlation Between FCD and Road Accidents to Identify Critical Areas

As the first step to individualize high-risk intersections, the KDE of accidents and FCD are correlated. In this case, KDE values from FCD can be used to identify streets or intersections with a higher risk of accidents, based on the assumption that FCD could be used as a surrogate safety measure.

Accordingly, the KDE was applied to analyze the spatial distribution of incidents and FCD data (acceleration and deceleration rates higher than threshold values), excluding, employing physical barriers, buildings and green spaces and therefore determining the values of densities relating to the road network (see Fig. 4).

This method enabled an accurate analysis and the identification of areas with elevated concentrations of anomalous/critical FCD by accounting for the influence of barriers on the kernel density (see Fig. 5).



Fig. 4. Barriers (in grey), composed of building structures and vegetated areas.

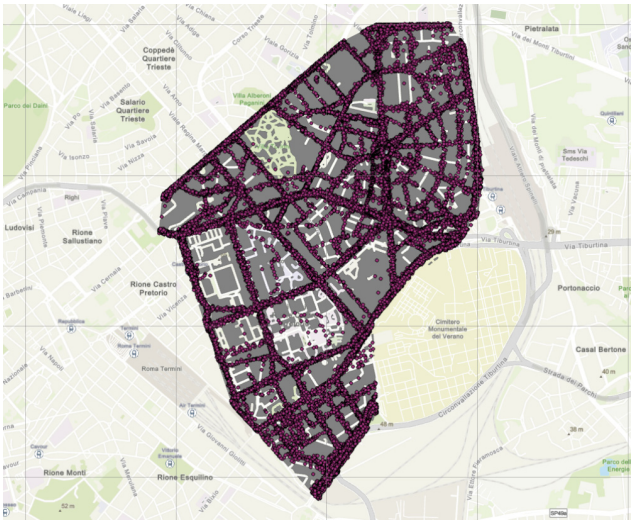

Fig. 5. Anomalies FCD values and barriers imported in GIS

The final output consisted of a georeferenced raster image, with each pixel representing a 10-m section of road infrastructure and containing the Kernel Density value (see Fig. 6), that is then compared and integrated with the other KDE for road accidents (see Fig. 7).

Kernel density values for both incident and FCD data are calculated and classified based on the mean and standard deviation of point values [14]. This classification helps identify areas that require more detailed investigation.



Fig. 6. KDE with barriers calculated for the FCD and visualization in GIS

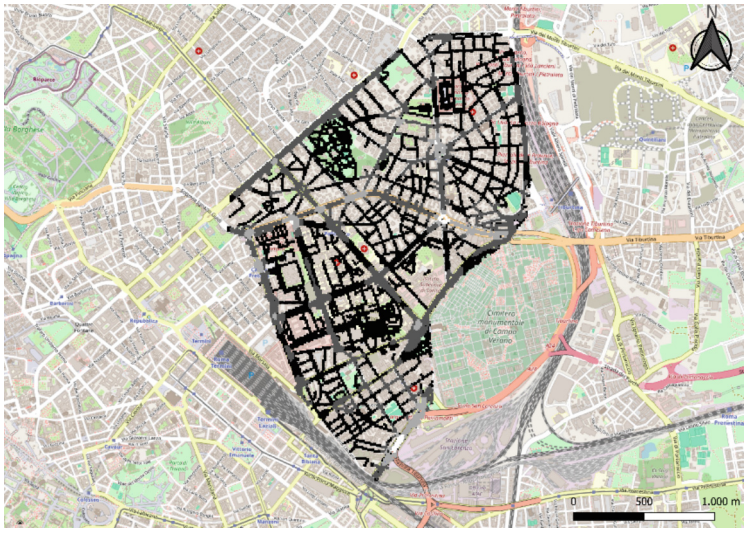

Fig. 7. KDE image with FCD values and barriers

A Python script classified data using the proposed threshold, while GIS software visualized risk levels to identify high-risk intersections or road sections.

In this study, the Pearson correlation coefficient was used to assess whether accident data hotspots aligned with those identified using FCD which was conducted for the entire study area. The coefficient was computed automatically using the 'r.covar' tool in QGIS,

utilizing filtered raster data from accident records and FCD. Results were interpreted according to established literature [21].

After calculating the value of the Pearson correlation between FCD and accidents data, we have obtained the value of 0.61 and based on what we have mentioned in the previous section, this value indicates a moderate correlation. As a result, the use of FCD is a statistically significant method to outline the most relevant road critical points.

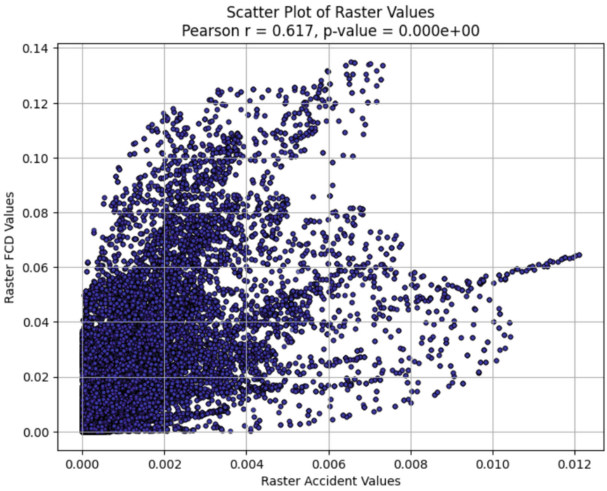

Fig. 8. Scatter Plot of Raster Values

According to the previously mentioned danger level classification (paragraph 2.2.), the percentage distribution of the FCD-based risk levels in the Nomentano Tiburtino district is as follows in Table 1.

Table 1. Percentage distribution of risk levels in the Nomentano Tiburtino area

Risk Level	Percentage [%]
Level 1	63.36
Level 2	30.86
Level 3	5.20
Level 4	0.59
Level 5	0.00

Observing the results, risk levels 1 and 2 together exceed 90% of the total, while no point in the Nomentano Tiburtino area reaches level 5. However, levels 3 and 4 are interesting enough to be selected for further detailed investigation.

4.3 Pedestrian Crowding Results

In addition to previous analyses pedestrian crowding analysis has been carried out to evaluate exposure to risk and critical areas: in Fig. 8 the graphic results are reported and in red the most critical areas are shown.

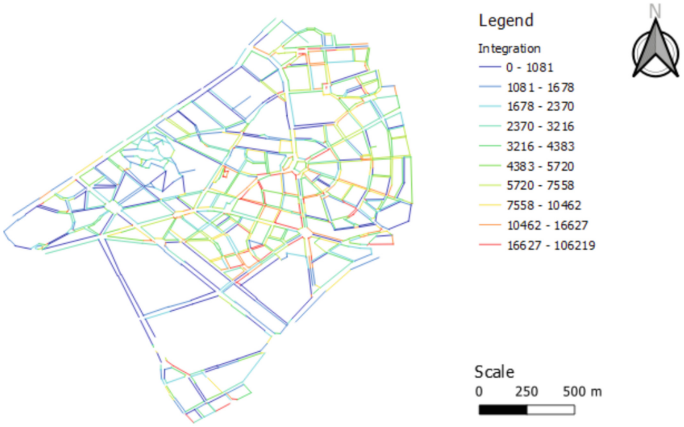

Fig. 9. Distribution of Integration on the Nomentano – Tiburtino in the context of pedestrian crowding analysis [22].

The analysis carried out is based on the evaluation of the Integration quantity which defines pedestrian crowding based on the geometric characteristics of the pedestrian network, in particular, an area with higher Integration will tend to attract pedestrians as it is well connected to the network.

However, for the present analysis, the value of Integration has been "corrected" with a weight that refers to the presence of shops along the pedestrian network, as it has been shown that this correction better represents the real situation [22].

The results obtained show that most of the areas with significant crowding (in red) are located in the central part of the study area.

4.4 Classification of Dangerous Road Intersections

With the analysis carried out on pedestrian crowding, it was possible to create a heatmap that could categorize areas from the least crowded to the most crowded.

The classification of the most hazardous sites is based on the results of three analyses aimed at identifying:

- A high concentration of accidents involving vulnerable road users;
- A high concentration of abnormal acceleration/deceleration events detected through FCD data;
- Pedestrian crowding.

The proposed aggregation is based on the following considerations:

- The significant weight assigned to findings related to the abnormal concentration of accidents involving vulnerable road users (pedestrians, cyclists, motorcyclists) recorded over the decade 2011–2020;
- The high relevance of the analysis results based on FCD data, considering that these data are regarded as potential predictors of accidents for the overall incident occurrence (moderate correlation between FCD data and accidents in the period 2018–2020);
- The lower relevance assigned to pedestrian crowding data, which is considered an additional potential factor contributing to accident occurrence.

Based on the above criteria, the weights for the Vulnerable User Accident Analysis with accident data, the FCD Analysis, and the Pedestrian Crowding Analysis (see Table 2) are reported and assigned to the different classes.

Table 2. Weights assigned to the Vulnerable User Accident Analysis carried out.

Class	Weight α	Weight β	Weight γ
<3	-	4	1
3–4	-	5	2
4–5	8	-	-

A comprehensive Risk Indicator (RI) is proposed as follows (Eq. 7):

$$\boldsymbol{RI = \alpha + \beta + \gamma} \tag{7}$$

where:

- $\alpha = 8$ for sites classified as 4–5 in terms of high accident concentration.
- $\beta = 5$ for sites classified as 3–4, and $\beta = 4$ for sites classified as 3, based on the concentration of abnormal acceleration/deceleration events detected through FCD data.
- $\gamma = 2$ for sites classified as 4 and 3–4, and $\gamma = 1$ for sites classified as < 3, based on pedestrian crowding levels.

Based on the value obtained from the risk indicator, sites are aggregated into the following four groups in Table 3.

For the identified groups, the predominant causes of accidents (further detailed in the following sections) are primarily the following:

- Road Surface Conditions: The intersections consist of streets with pavements made of different materials, such as asphalt and stone, leading to inconsistent road friction for vehicles. Numerous potholes further increase the risk of accidents, particularly for two-wheeled vehicles such as motorcycles and bicycles, which are more susceptible to losing control on uneven surfaces.
- Horizontal Signage: The condition of horizontal road markings is poor, with pedestrian crossings partially erased. This lack of clear markings can create confusion

Table 3. Classification of sites based on the risk indicator value and main common characteristics.

Group	Risk Indicator	Number of sites	Characteristics
1	>13	1	High concentration of VRU accidents and FCD data; moderate to high levels of pedestrian crowding
2	9–13	4	High concentration of VRU accidents and significant concentration of FCD data; high pedestrian crowding during certain hours of the day
3	5–8	6	Sites characterized by the absence of high concentrations of VRU accidents, with high or moderate concentrations of FCD data and moderate to high pedestrian crowding
4	<5	8	Sites characterized by the absence of high concentrations of VRU accidents and the absence of high or moderate concentrations of FCD data; moderate to high pedestrian crowding

for both drivers and pedestrians, increasing the likelihood of accidents, especially in low-light conditions or during inclement weather.

- Illegal Parking: High presence of illegally parked vehicles, particularly near pedestrian crossings. These parked vehicles can obstruct drivers' visibility of pedestrians, increasing the risk of accidents as pedestrians attempt to cross the street.
- Pedestrian and Vehicle Interactions: Public transport stops and pedestrian crossings are located in positions that do not prevent illegal pedestrian behaviors (jaywalking). The increased pedestrian presence, combined with the aforementioned poor visibility and road conditions, further heightens the risk of pedestrian-vehicle collisions.

4.5 Intervention Effectiveness Matrix

Several key interventions are necessary to enhance road safety and mitigate accident risks. Improving road surface conditions by repairing potholes and ensuring uniform pavement materials can reduce hazards, particularly for two-wheeled vehicles. Enhancing horizontal signage, including repainting pedestrian crossings, will improve visibility and clarity for both drivers and pedestrians. Enforcing regulations against illegal parking near crossings is crucial to maintaining clear sightlines. Additionally, optimizing the placement of public transport stops and pedestrian crossings can help discourage unsafe pedestrian behavior, reducing the likelihood of collisions. These measures collectively address critical safety concerns and improve overall urban mobility.

Following the identification of critical sites in the Nomentano-Tiburtino Area an original methodology to evaluate the best safety improving measures was developed. The core of this methodology is based on an *"Intervention Effectiveness Matrix"*.

The matrix, which follows, represents an analysis of the causes and the related mitigation interventions, based on Crash Modification Factors (CMF).

The CMF values were obtained from the consultation of the "Highway Safety Manual" (HSM) [23], the CMF Clearinghouse database [24] and "The Handbook of Road Safety Measures" [25] using the following values as classification criteria:

– CMF $\geq$ 0.8: Moderate effectiveness of the intervention.
– CMF $<$ 0.8: High efficacy of the intervention.

The CMF values reported represent average values calculated from the individual CMFs, which may vary for each intervention according to specific factors related to the context and the peculiar characteristics of the intervention itself; however, a filter has been applied to the type of area of interest by setting it as "Urban and Suburban" (see Fig. 9).

Subsequently, targeted interventions were identified for each site under investigation, based on the matrix shown above.

Based on the causes, through the analysis of road accidents, FCD data and finally pedestrian crowding, it was possible to assign priority to interventions.

The prioritization process has been divided into the following phases:

First of all, by consulting the interaction matrix, the most appropriate interventions were associated with the specific causes detected for each site.

The interventions were divided into two main categories:

- ***Priority***: interventions that see two or more interactions between the various causes;
- ***Secondary***: interventions act on a single cause without interaction with others.

In light of the above, therefore, the intervention strategy provides for priority to be given to interventions in the Priority category, postponing the implementation of those classified as Secondary.

In addition, within the respective "Priority" and "Secondary" categories, the interventions that, from the CMF study, were found to be the most effective (in green), while the least effective (in orange) will be carried out only after the former (Fig. 10).

While several studies have employed stand-alone approaches based on accident data, FCD, and pedestrian crowding, there remains a gap in the literature regarding the analysis of integrated methods, underscoring the novelty of the proposed approach. In this context, the proposed method and the obtained results are promising, paving the way for more advanced analyses to validate its effective application in additional intersections with varying configurations.

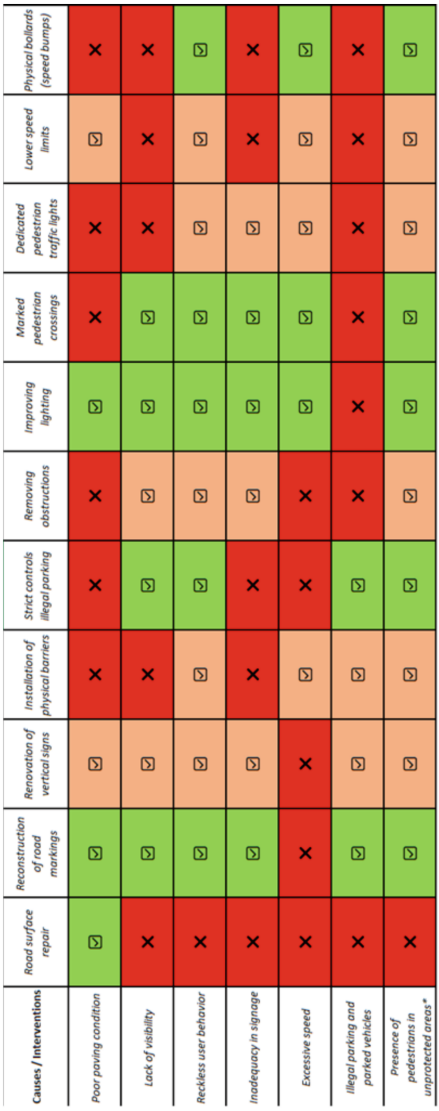

Fig. 10. Description of Intervention Effectiveness Matrix. The matrix is read through the following visual scale: Green (Effective intervention), Orange (Moderate efficacy), Red (Not effective Intervention).

5 Conclusions

The proposed procedure and risk indicator provide a systematic approach to identifying high-risk areas for vulnerable road users by integrating accident data, FCD analysis, and pedestrian density. This method stands as a starting point for a more comprehensive methodology understanding of accident-prone locations, supporting data-driven

decision-making for targeted safety interventions. Furthermore, the findings can guide urban planning and road maintenance strategies to enhance overall traffic safety.

These findings can serve as a foundation for future on-site analyses and to promote regular maintenance interventions, such as the restoration of signage or the improvement of road conditions. Addressing these issues could significantly enhance road safety in the areas under investigation.

The study focuses on identifying risks and critical road areas to assist decision-makers in developing solutions for safe and efficient mobility, particularly for vulnerable users (VRU) and individuals with reduced mobility (PMR). This process involves the use of GIS software and techniques and statistical analyses for data handling.

Accident data was enriched with details such as location, date, time, and accident dynamics. This data was then incorporated into GIS to examine its distribution to vehicular traffic patterns. Then Kernel density estimation was applied to further identify the most hazardous intersections and explore correlations between driver behavior and accident rates.

Comparing Kernel density data for accidents with FCD-based data revealed significant overlap in high-risk areas. The statistical analysis confirmed a moderate positive linear correlation between the two datasets, with a correlation coefficient of 0.61.

Alongside, pedestrian crowding analyses were carried out to identify the most crowded areas, characterized by a high level of exposures. In the risk evaluation field, vulnerability, hazard, and exposures are essential to evaluate risk values.

For each of the analyses made, a weight coefficient is applied to evaluate Risk Indicator (RI) for several areas: the higher the RI, the higher the risk levels. Once the most critical areas are identified, according to RI, several interventions are proposed and organized in an Intervention Effectiveness Matrix. The level of effectiveness is assessed by evaluating the Crash Modification Factors, associated with a single intervention: this factor indicates how the probability of road accident will decrease, so the lower the CMF, the lower the probability. The proposed approach and the obtained results are promising and pave the way for more advanced analyses to validate its effective application in additional intersections with varying configurations. This initial achievement lays the foundation for future studies that will refine and expand the methodology, ensuring its robustness and applicability across different types of road environments, VRU and traffic scenarios.

Acknowledgments. The research leading to these results has received funding from Project "Ecosistema dell'innovazione Rome Technopole" financed by the EU in the NextGenerationEU plan through MUR Decree n. 1051 23.06.2022 - CUP H33C22000420001. This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

References

1. Federal Highway Administration (FHWA): Safe System Strategic Plan. https://highways.dot.gov/safety/zero-deaths/safe-system-approach-toward-zero-traffic-deaths. Accessed July 2024
2. Vision Zero. https://visionzeronetwork.org/. Accessed July 2024
3. Toward Zero Deaths. https://www.towardzerodeaths.org/. Accessed July 2024
4. Road to Zero. https://www.nsc.org/road/resources/road-to-zero/road-to-zero-home. Accessed July 2024
5. TIME, O. C. A. A. Making Our Roads Safer
6. U.S. Department of Transportation. Federal Highway Administration. Making our Roads Safer. One Countermeasure at a time. 28 Proven Safety Countermeasures that offer significant and measurable impacts to improving safety. https://safety.fhwa.dot.gov/provencountermeasures/pdf/FHWA-SA-21-071_PSC%20Booklet_508.pdf. Accessed July 2024
7. U.S. Department of Transportation, Federal Highway Administration. Proven Safety Countermeasures. https://highways.dot.gov/safety/proven-safety-countermeasures. Accessed July 2024
8. Jancey, J., Cooper, L., Howat, P., Meuleners, L., Sleet, D., Baldwin, G.: Pedestrian and motorized mobility scooter safety of older people. Traffic Inj. Prev. **14**(6), 647–653 (2013)
9. Lima, J.P., Machado, M.H.: Walking accessibility for individuals with reduced mobility: a Brazilian case study. Case Stud. Transp. Policy **7**(2), 269–279 (2019)
10. Gaglione, F., Cottrill, C., Gargiulo, C.: Urban services, pedestrian networks and behaviors to measure elderly accessibility. Transp. Res. Part D: Transp. Environ. **90**, 102687 (2021)
11. Kwon, K., Akar, G.: People with disabilities and use of public transit: the role of neighborhood walkability. J. Transp. Geogr. **100**, 103319 (2022)
12. Roma Capitale Road Accident data. https://www.comune.roma.it/web/it/home.page. Accessed 28 Feb 2025
13. Xie, Z., Yan, J.: Kernel density estimation of traffic accidents in a network space. Comput. Environ. Urban Syst. **32**(5), 396–406 (2008)
14. Bassani, M., Rossetti, L., Catani, L.: Spatial analysis of road crashes involving vulnerable road users in support of road safety management strategies. Transp. Res. Procedia **45**, 394–401 (2020)
15. Simons-Morton, B.G., Zhang, Z., Jackson, J.C., Albert, P.S.: Do elevated gravitational-force events while driving predict crashes and near crashes? Am. J. Epidemiol. **175**(10), 1075–1079 (2012). https://doi.org/10.1093/aje/kwr440
16. Santilli, D., D'apuzzo, M., Evangelisti, A., Nicolosi, V.: Towards sustainability: new tools for planning urban pedestrian mobility. Sustainability **13**(16), 9371 (2021)
17. D'Apuzzo, M., Santilli, D., Evangelisti, A., Nicolosi, V., Cappelli, G.: Estimation of pedestrian flows in urban context: a comparison between the pre and post pandemic period. In: Gervasi, O., Murgante, B., Misra, S., Ana, M.A., Rocha, C., Garau, C. (eds.) Computational Science and Its Applications – ICCSA 2022 Workshops: Malaga, Spain, July 4–7, 2022, Proceedings, Part IV, pp. 484–495. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-10542-5_33
18. Comune di Roma: Roma Capitale - Annuario statistico 2022, CAP.1 Territorio e climatologia (2022). https://www.comune.roma.it/web-resources/cms/documents/01_Territorio_Annuario_2022.pdf
19. Grandi Stazioni: Roma Termini. https://www.grandistazioni.it/it/le-nostre-stazioni/roma-termini.html. Accessed Feb 2025
20. A.S. Roma S.p.A: Piano economico-finanziario nuovo stadio di Roma-Progetto di fattibilità tecnico ed economica (2022). http://www.urbanistica.comune.roma.it/images/stadio-roma/elab2022/03-00-piano-economico.pdf

21. Evans, J.D: Straightforward Statistics for the Behavioral Sciences. Brooks/Cole Publishing Company (1996)
22. Naranni S., Cappelli G., D'Apuzzo M., Nicolosi V.: Estimation of pedestrian flows with open-source crowding data: integrated model between configurational and physical approach in Nomentano-Tiburtina district, Rome. In: The 25th International Conference on Computational Science and Its Applications., Istanbul, Turkey. 30 June- 3 July 2025 (2025, in press)
23. National Research Council (US). Transportation Research Board. Task Force on Development of the Highway Safety Manual, & Transportation Officials. Joint Task Force on the Highway Safety Manual. Highway safety manual, vol. 1. Aashto (2010)
24. Clearinghouse Database. Crash Modification Factors (CMFs). https://cmfclearinghouse.fhwa.dot.gov/. Accessed Feb 2025
25. Elvik, R., Høye, A., Vaa, T., Sørensen, M.: The Handbook of Road Safety Measures. Emerald Group Publishing Limited (2009)