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Accident Risk reduCtion of vulnerAble RoaD usErs: an interdisciplinary – multiperspective approach (ARCADE)

Deliverable 1

WP1 – Observational investigations (Method #1)

. T1.1 Identification of HRL in the three municipalities

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WP1 – Observational investigations (Method #1).

T1.1 Identification of HRL in the three municipalities based on already available data and studies. Selection of three case studies (all RUs).

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1 Introduction

This deliverable aims to summarize the results obtained from the three Research Units (RUs) regarding the activities of Work Package 1 in Task 1. The objective of this task was to identify Hazardous Road Locations (HRLs) for the municipality involved in the project (Rome, Turin and Padua). HRLs are locations that have a higher risk of collision than other similar locations (Loo & Anderson, 2015). These locations fall within the urban perimeter of the cities and count a relevant number of collisions involving Vulnerable Road Users (VRUs) such as pedestrians, cyclists, motorcyclists and, more recently, new electric two-wheelers (E2Ws). HRL analysis is divided in three main steps: (i) identification, (ii) ranking and (iii) selection to implement safety treatment.

The identification of HRLs in the three cities is the initial step in the ARCADE project development. The HRLs serve as points of interest for studying safety issues and exploring potential countermeasures to improve the safety of VRUs in these sites, in line with the Horizon Europe Research Framework ([1]).

Once the HRLs have been identified, on site observations will be carried out according to Task 1.2. These analyses will help to identify typical conflicts and the frequency of interactions between VRUs and drivers. Analyses will be performed using image analysis software and algorithms (see Task 1.3) to evaluate Surrogate Safety Measures (SSMs, Task 1.4). In addition to the evaluation of conflicts and interactions between VRUs and drivers, the results obtained will also be used to validate the outcomes of driving simulations for cars, motorcycles and bicycles, as well as pedestrian simulations in Work Package 2.

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[1] Cluster 5 – Expected Impact No. 26, Safe, seamless, smart, inclusive, resilient, climate-neutral, and sustainable mobility systems for people and goods thanks to user-centric technologies and services, including digital technologies and advanced satellite navigation services

2 Methods

The availability of official crash databases allowed Politecnico di Torino and Università degli Studi ROMA TRE to analyse the spatial distribution of collision data in the municipalities of Turin and Rome. Thanks to the precise geolocation of the crash events, a pattern analysis was performed. First, the spatial interaction of point events, based on the distance of the points from each other (i.e., distance-based methods), was evaluated using the Nearest Neighbour analysis to check whether the road collisions had a cluster configuration. HRLs were then detected by using the Kernel Density Estimation, one of the most popular density-based methods for identifying areas of high collision density.

In the absence of comprehensive data for the entire municipality, the University of Padua identified HRLs thanks to the recommendations from the municipal administration and the local traffic police. Insights and local knowledge of these authorities allowed this RU to identify critical areas with safety concerns. Although no spatial statistical analysis was performed, HRLs were identified based on expert input and practical observations.

2.1 Nearest Neighbour analysis (distance-based methodology)

The Nearest Neighbour analysis is a descriptive method commonly used to analyse point pattern datasets by examining the distances between points. It compares the observed distances with those expected in a randomly distributed scenario, to determine the potential tendency of the observed point pattern towards clustering or dispersion. This comparison is defined by the Nearest Neighbour Index (NNI) as follows:

$$NNI = \frac{d_{obs}}{d_{exp}}$$

where d_{obs} is the “nearest neighbour distance”, i.e., the sum of the distances from each point to its nearest neighbour divided by the number of points, and d_{exp} is the “expected mean distance”, i.e., the distance from each point to its nearest neighbour if points were under the complete spatial randomness (CSR) hypothesis. The NNI identify the three different patterns shown in Figure 1. NNI < 1 indicates a clustered pattern, NNI around 1 indicates a random pattern, NNI > 1 indicates a regular (or uniform) pattern.

Although an NNI may indicate clustering or dispersion in a pattern of points, the observed clustering or dispersion may be due to chance and therefore not statistically significant. The null hypothesis H_0 of the statistical test states that the observed points are randomly distributed. *Z*-scores and *p*-values are used to determine whether the null hypothesis can be rejected, confirming the significance of the clustering or dispersion (see the example of the results obtained by using GIS software in Figure 2).

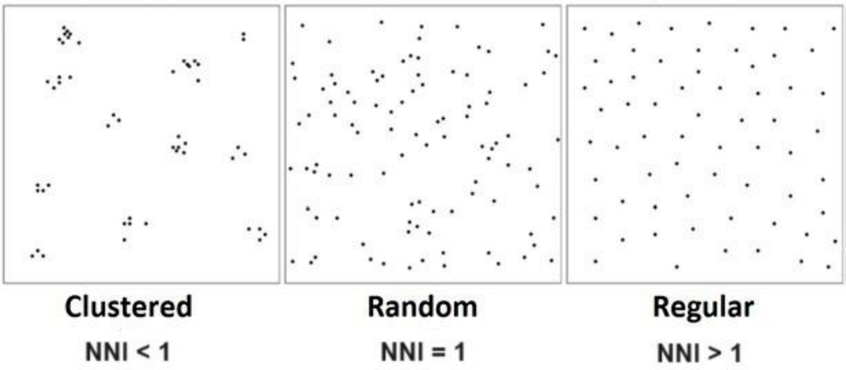
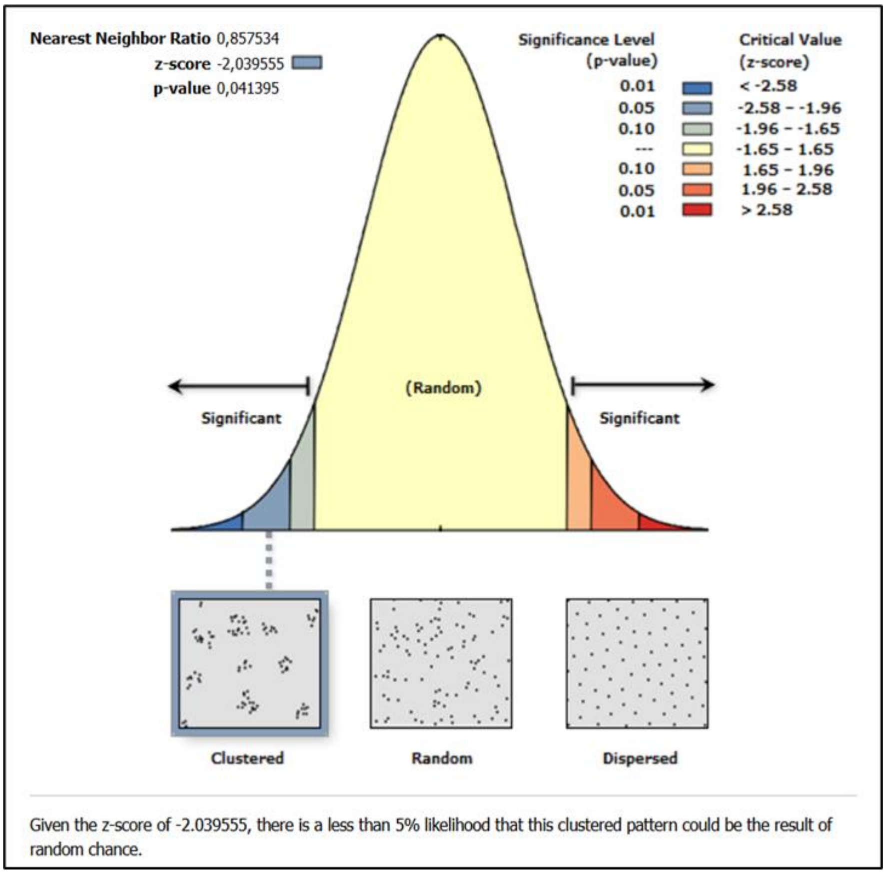


Figure 1. Different crash pattern based on Nearest Neighbour Index analysis.



Given the z-score of -2.039555, there is a less than 5% likelihood that this clustered pattern could be the result of random chance.

Figure 2. Example of the results of the Nearest Neighbour analysis.

2.2 Kernel Density Estimation (density-based methodology)

The Kernel Density Estimation (KDE) is a non-parametric method to estimate the probability density function of road collisions based on the kernel function. This method enables to evaluate the location of clusters, i.e., areas with high collision densities, the so-called “black zones” or “hotspots” or HRLs. Considering each collision as a point, the KDE involves (i) placing a symmetric surface (i.e., the kernel function) over each point, (ii) evaluating the distance from the point to a reference location based on a mathematical function and (iii) summing the value for all the surfaces for that reference location. This process is repeated for successive points (Fotheringham et al. 2000). The result is a smooth and continuous surface which indicates in each point the probability of crash occurrence based on historical data (see Figure 3).

The kernel function defines the shape of the surfaces to be placed over the individual observations (i.e., the road collisions) within a given threshold distance from the location where the density estimate is made. This threshold is the bandwidth, and it determines the kernel function width and the radius of each circular neighbourhood around each feature point.

Among the many possible kernel functions, the Quartic and Gaussian kernel functions were considered in the analyses. The kernel density function used in the analyses follows:

$$f(u,v) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{d_i}{h}\right)$$

where *f(u, v)* is the density estimate at the location (u, v), *n* is the number of observations, *h* is the bandwidth (or kernel size or smoothing parameter), *K* is the kernel function, d_i is the distance between the location (u, v) and the location of the *i*th observation. It is worth noting that the bandwidth affects the results (i.e., the larger the bandwidth, the larger the area of the HRLs), and it must be shorter than the average distance between intersection in the analysed (sub-)network, in order to avoid that the probability of a crash occurrence in a road element could be transferred to adjacent elements (in other term, the probability should be distributed within the same element where the crash occurred).

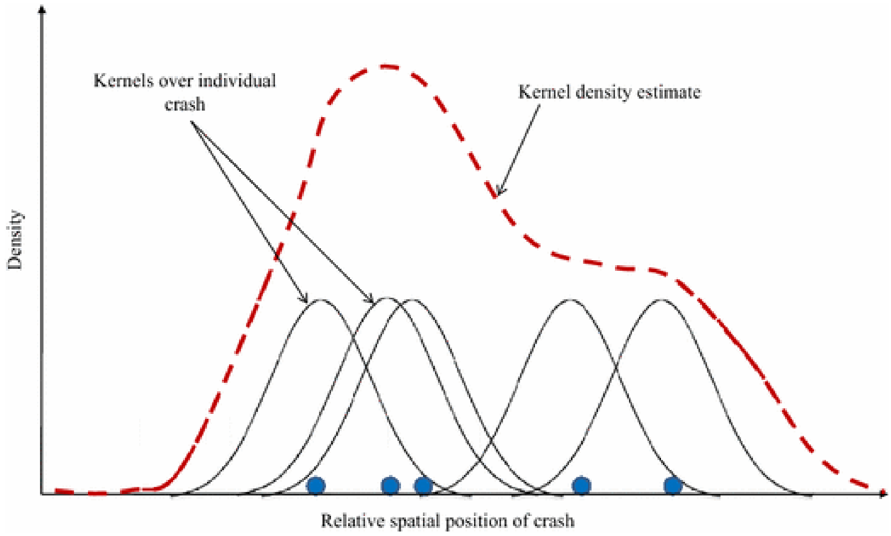


Figure 3. Example of KDE for a one-dimensional case.

A heat map is typically produced using GIS software (Fig. 4). The heat map is a graphical representation of the spatial distribution of data, with colour scales indicating different density ranges. To identify the HRLs, a statistical criterion was chosen to identify dangerous sites. As collisions are random events, a site is defined as hazardous if the frequency of road collisions is significantly higher than expected with respect to a pre-determined level of significance (see Figure 4). The two analyses shown in Figure 3 differ in the way distances are considered: in the first figure (Planar KDE), distances are estimated along straight lines, while in the second (KDE with building constraints) distances take into account spatial constraints imposed by the presence of buildings and non-road surfaces, with distances and relative probabilities estimated and quantified only for those surfaces where crash events are likely to occur.

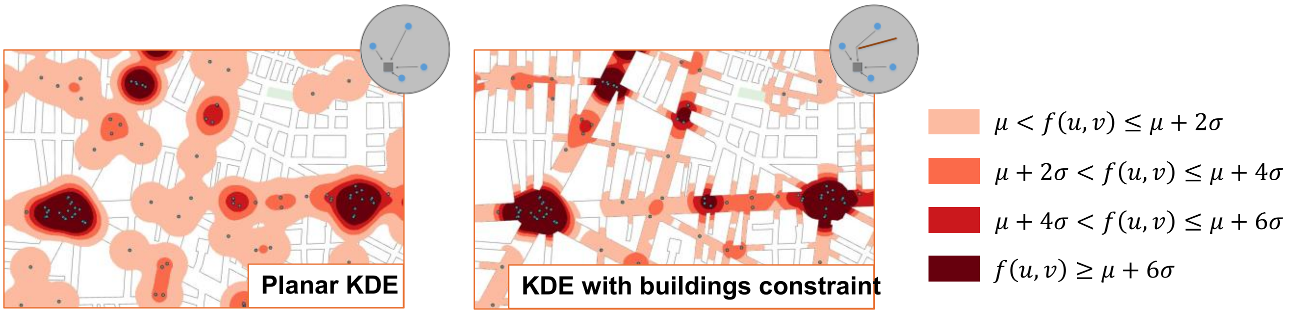


Figure 4. Example of heat maps produced with a KDE analysis of road collisions.

2.3 Alternative methods for HRL identification (Università di Padova)

As anticipated (page 3), the absence of comprehensive data for the Padua municipality lead Padua RU to solely rely on incidental data and recommendations from the municipal administration and the local traffic police. Indeed, no notable information was available for a quantitative analysis of critical traffic areas, consequently the identification of Padua's HRL was based on insights and local knowledge. The local traffic police listed several potential sites of interest, allowing the RU to identify the specific HRL based on (i) traffic intensity in each site; (ii) the number of critical events involving VRUs in each site and (ii) the specific site structure, for limiting the risk of simulation sickness inside the CAVE virtual environment. Four sites of major interest were selected from the first group, which we will name: "Saracinesca" (reference location: 45°23'56.8"N 11°51'51.7"E); "Rondò Reni" (reference location: 45°26'17.1"N 11°53'35.9"E); "Ariosto" (reference location: 45°24'15.5"N 11°54'02.5"E); and "Gattamelata-Modena" (reference location: 45°23'59.8"N 11°53'15.4"E). Although no spatial statistical analysis was performed, HRLs were identified based on reference rules described above, expert input and practical observations. The decisional process led the RU to the selection of the intersection between Via Gattamelata and Via Modena as HRL for the ARCADE project. Via Gattamelata is an important road artery of the city, characterized by heavy traffic during peak hours (7:00 – 9:30; 17:30 – 20:00). Available incidental data on the four sites referred to the last 10 years of traffic mobility and highlighted an overall high number of accidents involving VRUs (~ 75%). Compared to "Gattamelata-Modena" (n = 34) and "Saracinesca" (n = 36), "Rondò Reni" had a limited number of accidental data (n = 29), while accidents related to the "Ariosto" site (n = 54) were almost solely referred to accidents involving the VRU category of cyclists. Both "Saracinesca" and "Gattamelata-Modena" had a relevant proportion of VRU-involving accidents on the total amount of cases (respectively 78% and 70%), but the "Gattamelata-Modena" site was preferred considering the limited risk to incur in simulation sickness-related symptoms when simulating roundabouts in the CAVE virtual environment. The 56% of the reported accidents on this site happened in proximity of road crossings and the intersection. Only 7 events (20%) were reported concurrently to rainy weather. The 38% of the events took place during heavy traffic. Of the 34 accidents investigated on the selected site, 20% involved pedestrians, 35% involved motorcyclists, while 60% involved cyclists.

Interestingly, the selected site possesses specific characteristics on the zebra crossing area, such as a red-coloured concrete in correspondence of the intersection and the pedestrian crossing area, a non-separated bicycle lane from the vehicle lane with no road curbs. At the intersection area, the road lane “merges” with the intersection-coloured area, potentially causing a reduced identification on specific road users’ lanes for pedestrians, cyclists and drivers. At the intersection, vehicles have only the possibility to turn right in secondary roads but not left, because of the presence of a road separator between the two lanes. Overall, road lightning seems also limited during the night and there is no lightning system dedicated to the pedestrian crossing itself. Moreover, previous road signs (such as temporary zebra crossings in yellow) are still visible at the intersection.

Streetview of the HRL selected from the Padua RU (“Gattamelata-Modena”).

3 Results

3.1 Case study 1: Turin

For the identification of HRL in Turin, the ISTAT crash dataset was used. The dataset includes road collisions in the period 2006-2020, and spatial analysis was applied using both distance-based and density-based methods. Attention was also focused on crash events involving VRUs.

Turin has a population of 846,926 inhabitants (ISTAT, January 2024), making it the fourth most populous city in Italy, after Rome, Milan, and Naples.

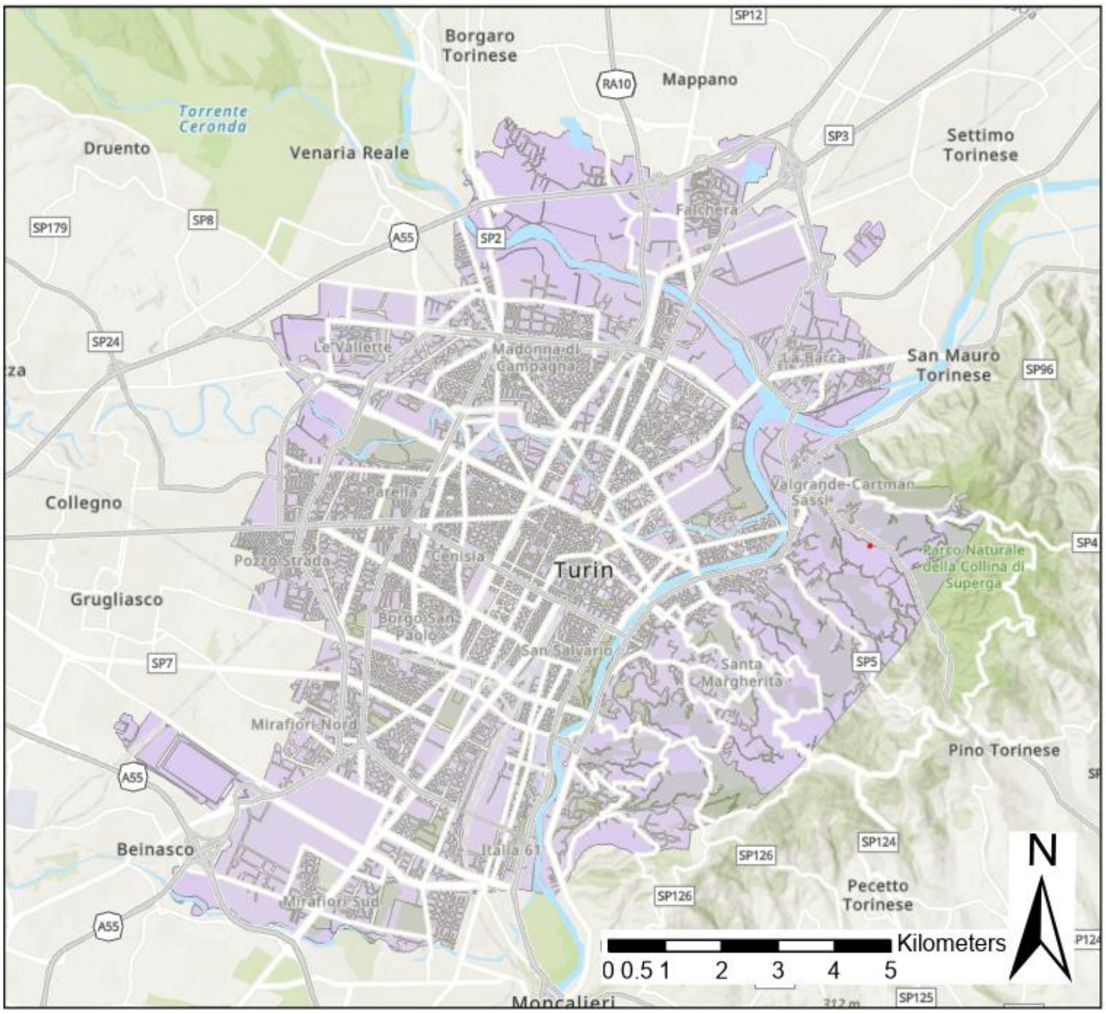


Figure 5. Map of the city of Torino.

3.1.1 Descriptive statistics

For the years 2006-2010, the crash database provides the location of each event according to the nearest address number only. By converting the declared address into geographical coordinates, 21,719 records were obtained for the period 2006-2020 with at least one VRU involved. This number represents 42.52% of the total number of collisions in the municipality. 96.45% of the data (20,948) were included because the collisions were geolocated, while 3.55% (771) were excluded.

First, the collision data were evaluated at the regional (Piedmont), provincial (Turin) and municipal (Turin) levels (Figure 6). The number of VRU collisions within the city of Turin is also shown. 93,149 out of 179,601 collisions (51.9%) in the Piedmont region were recorded in the province of Turin, and 51,085 (28.4%) were in Turin. A decreasing trend in the number of collisions is observed for all collision categories over the years.

The analysis was further developed in three other temporal dimensions: (i) each quarter of the year (Table 1), (ii) daily (Figure 7) and (iii) by considering the time hour of the day (Figure 8).

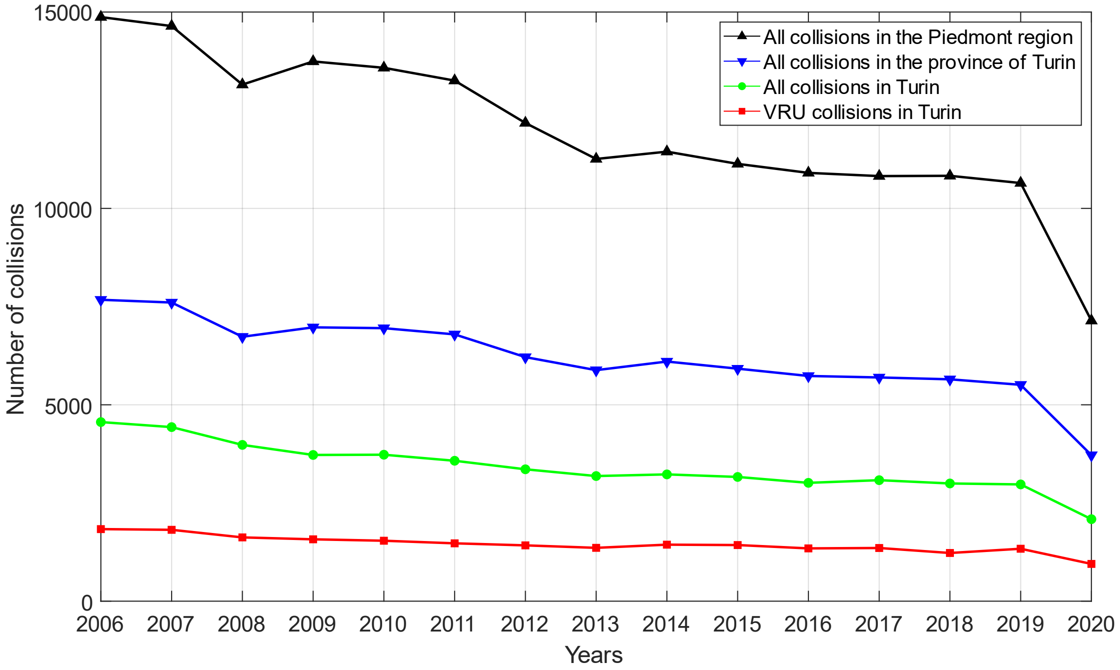


Figure 6. Number of collisions between 2006 and 2020.

Table 1. Collision frequency in Turin per quarters for all road collisions and for VRU road collisions (the quarter that has the highest collision frequency for each year is highlighted in bold).

	All road collisions				VRU road collisions			
	1st quarter	2nd quarter	3rd quarter	4th quarter	1st quarter	2nd quarter	3rd quarter	4th quarter
2006	1 050	1 199	1 045	**1 266**	347	**537**	451	500
2007	1 080	**1 244**	997	1 111	372	**545**	454	446
2008	1 012	**1 058**	892	1 017	379	**453**	395	397
2009	823	**1 051**	864	985	312	**466**	399	398
2010	804	997	903	**1 025**	273	**449**	434	383
2011	790	**1 029**	848	908	281	**476**	380	336
2012	775	**962**	743	878	274	**430**	357	360
2013	750	815	715	**906**	264	**369**	**369**	356
2014	761	**876**	724	867	285	**425**	353	376
2015	706	**886**	724	847	274	**435**	349	371
2016	697	782	714	**820**	263	**381**	356	344
2017	699	829	696	**857**	285	**399**	320	350
2018	668	811	645	**873**	224	341	313	**349**
2019	732	757	653	**831**	297	334	301	**403**
2020	528	364	**674**	522	209	162	**326**	252
2006-2020	11 875	13 660	11 837	**13 713**	4 339	**6 202**	5 557	5 621
2006-2020	**51 085**				21 719			

According to Table 1, the critical quarter for "all road collisions" has been the fourth (i.e., September – December), while the most critical quarter for "VRU road collisions" has been the second (i.e., May – August). These results suggest that while the worsening weather conditions associated with the increase in traffic due to the return from the summer period and the return to school may have affected the fourth quarter crash data for all road users. The peak of collisions involving VRUs in the spring period is due to the increase in traffic in this category as the warm season approaches. The data for the year 2020 must be evaluated considering the restrictions due to the COVID-19 pandemic that affected the movements of citizens in the March-June period.

Figure 7 shows the daily distribution of road collisions. The highest collision frequency had been recorded on Friday for both types of events (with 8022 collisions for all users, 3621 collisions for VRUs only). The lowest collision frequency had been recorded on Sunday (with 5811 and 1529 collisions, respectively).

Figure 8 shows the distribution of the number of collisions within the day. The data showed two peaks, one between 8 and 9 am and the main one between 5 and 6 pm and 6 and 7 pm. These values are in line with the daily traffic peaks observed in Italian urban areas, highlighting the critical periods coinciding with the start and end of working hours.

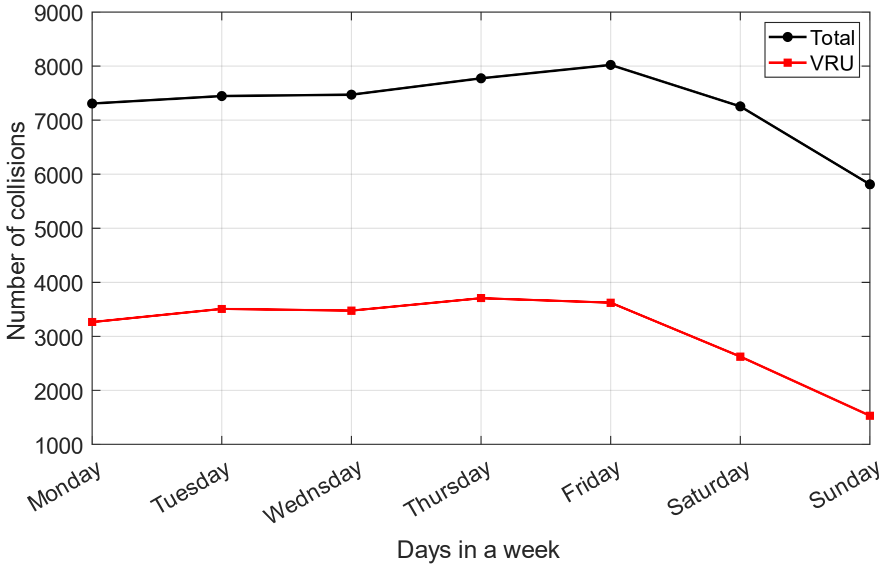


Figure 7. Collision frequency in Turin per day in a week (2006-2020 crash data).

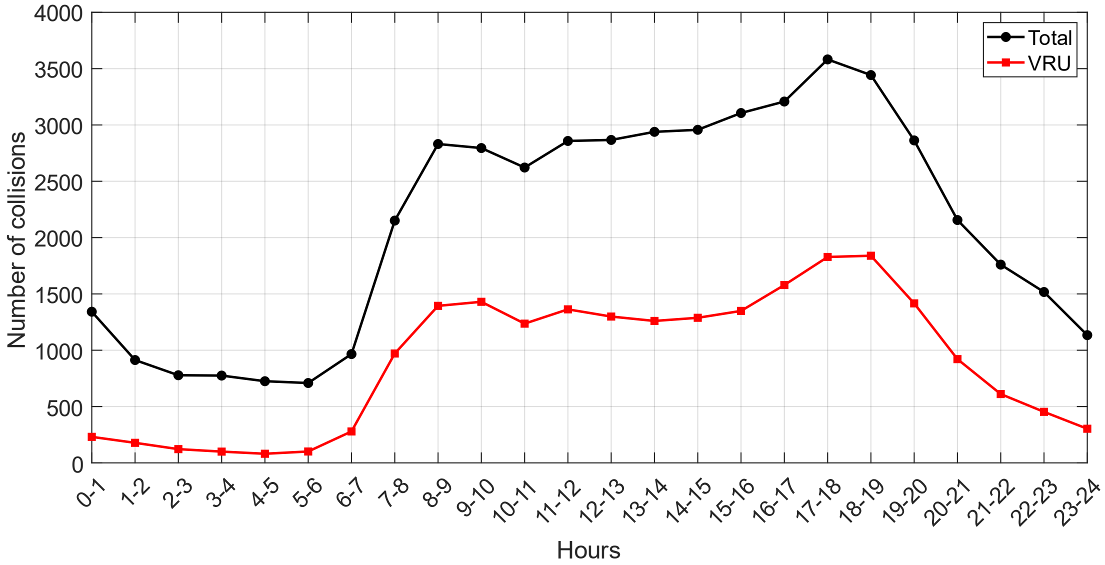


Figure 8. Collision frequency in Turinper hours in a day (2006-2020 crash data).

Finally, Figure 8 shows the distribution of traffic collisions involving VRUs. In Turin, the VRUs most involved are motorcyclists and pedestrians. It is worth noting that over the 15 years of observation (2006-2020), there is a downward trend in events, which has been faster for motorcyclists. However, the only category that has not shown a decreasing trend has been cyclists. This is due to the significant increase in their presence resulting from the national and local initiatives to support cycling, which is still growing year by year.

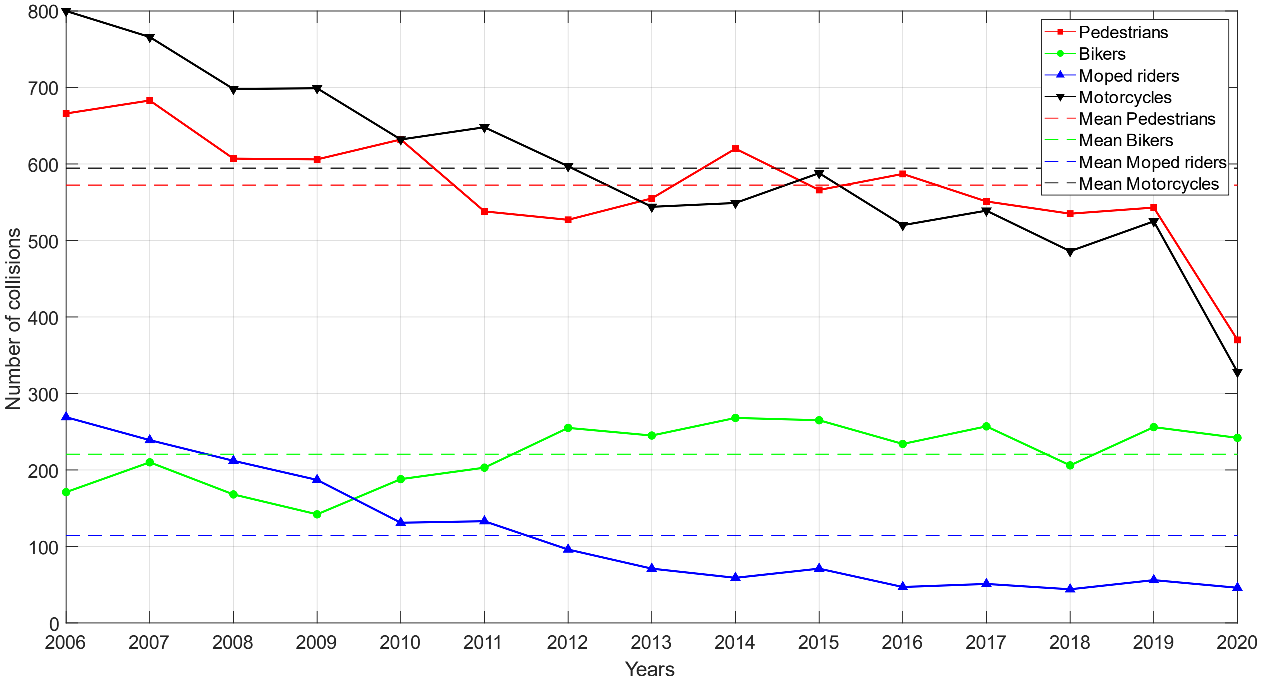


Figure 9. Collision frequency in Turin per year involving at least one VRU sub-category (2006-2020).

3.1.2 Nearest Neighbour analysis

A study period of three years was chosen to group crash data to avoid the influence in statistical fluctuations in the data on road elements. Table 2 shows the estimation of NNI distinguishing sub-categories of VRUs. NNI values constantly lower than 1 indicated the presence of clustered data, while z-score and associated p-values always lower than 0.001 confirms that such estimation is statistically significant for all VRU subcategories.

Table 2. Nearest Neighbour analysis results for different VRU subcategories.

	Pedestrians			*Velocipedes, scooters & bicycles*			*Motorcycles & mopeds*		
	NNI	*z-score*	*p value*	*NNI*	*z-score*	*p value*	*NNI*	*z-score*	*p value*
2006-2008	0.50	-40.97	<0.001	0.74	-11.00	<0.001	0.48	-52.15	<0.001
2009-2011	0.52	-37.88	<0.001	0.70	-12.87	<0.001	0.51	-44.61	<0.001
2012-2014	0.55	-35.61	<0.001	0.65	-18.45	<0.001	0.55	-37.54	<0.001
2015-2017	0.54	-36.60	<0.001	0.69	-16.35	<0.001	0.55	-36.37	<0.001
2018-2020	0.54	-33.16	<0.001	0.67	-16.57	<0.001	0.62	-27.83	<0.001

3.1.3 Spatial identification of clusters (KDE)

By analysing the geographical data containing all the collisions involving VRUs in the period 2006-2020 in Turin, the spatial identification of clusters was performed to identify HRLs using the Kernel Density Estimation (KDE). The density area considers the presence of buildings as a constraint for evaluating the distances between events. A bandwidth of 100 m was chosen. Finally, all the heat bands with a density value $f(u, v) > \mu + 6\sigma$ were selected as HRLs.

Figure 10 shows the HRLs for all VRUs. It is worth noting that the crashes were mainly concentrated at intersection along main corridors. The figure indicates that (i) Corso Vittorio Emanuele II, (ii) the corridor of Corso Lecce, Corso Trapani and Corso Siracusa, (iii) the corridor of Corso Mortara, Corso Vigevano and Corso Novara, and (iv) the corridor of Corso Turati and Corso Unione Sovietica are more hazardous than others. In addition, HRLs were identified in some of the main squares of the city: Piazza Rivoli, Piazza Adriano, Piazza Bernini, Piazza Baldissera, Piazza Statuto, and Piazza Vittorio Veneto. In these large areas, different users interact at different speeds and, therefore, have a high number hazardous of conflict points. They are also the busiest areas in the city.

Figure 10. KDE results of VRU collisions in Turin in the period 2006-2020.

The HRL for pedestrians are shown in Figure 11a. Contrary to the overall VRU case, there were fewer corridors identified as dangerous: Corso Novara, Corso Giulio Cesare, Corso Racconigi, Corso Filippo Turati and Corso Maroncelli. These corridors have main road with wide carriageways (three lanes per direction), so pedestrians are exposed for long times to the interaction with vehicles, a fact that increases the risk of collision. Local problems were also identified in areas of greatest pedestrian activity like Rivoli, XVIII Dicembre, Vittorio Veneto, Baldissera and Robilant squares. Significant examples of hazardous intersections for pedestrians are those between Corso Maroncelli and Via Nizza, and Corso Maroncelli and Via Canelli (red circles in Figure 11a).

HRL for cyclists are represented in Figure 11b. The five HRLs for cyclists are Rivoli, Bernini, Statuto, and Baldissera squares, and intersections along Corso Vittorio Emanuele II, Corso Castelfidardo and Corso Inghilterra. All these HRLs are equipped with cycle paths in the service roads. As they are heavily used by these users, they were identified as HRLs.

Figure 11c shows the HRLs for motorcyclists, and Figure 11d shows the dangerous areas for motorcyclists and moped riders. The identified corridors, common to both cases, are Corso Vittorio Emanuele II, Corso Peschiera, Corso Bramante and the Corso Potenza, Corso Lecce and Corso Trapani corridor. There are some differences between the two cases in the squares identified. The most hazardous squares for the first sub-category of VRUs are Massaua, Rivoli, Adriano and Costantino il Grande squares (Figure 11c), while for the second sub-category there are two more squares in addition to these four: Derna and Pitagora (Figure 11d).

Heat maps identify critical zones at intersections along the main corridors of the city. For the general VRU category and for the sub-categories of pedestrians, cyclists, motorcyclists and moped riders together, an average of 25 critical points was identified. For cyclists, there are 5 main HRLs.

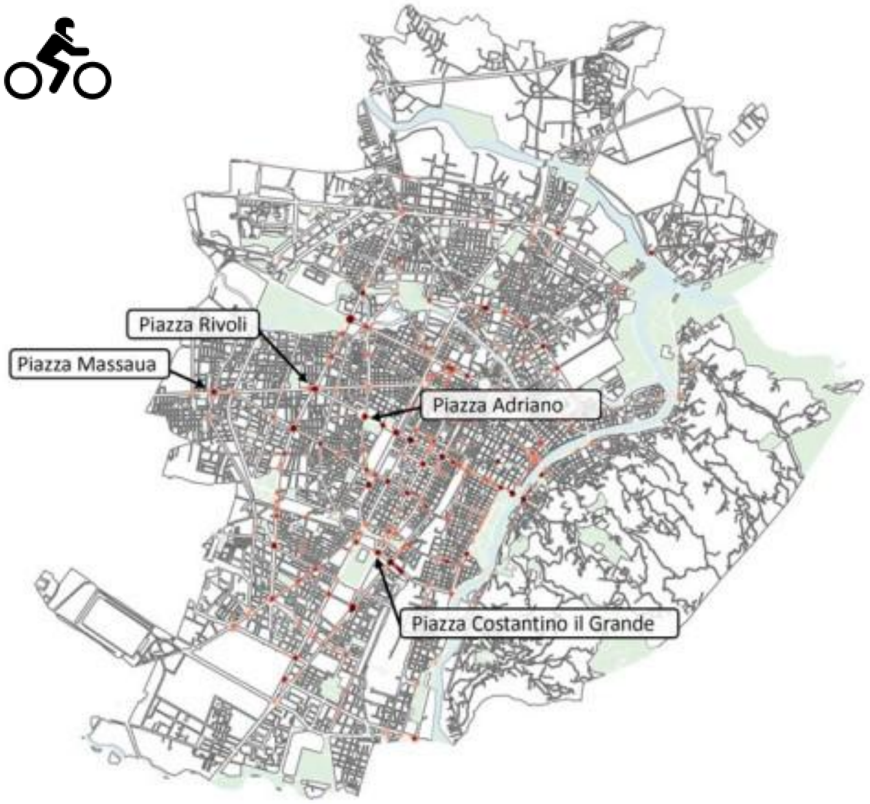
Because of the number of HRL along Corso Vittorio Emanuele II, the Politecnico di Torino will consider this corridor as the case study in the research activities to be carried out in the ARCADE project.


Piazza Baldissera
Piazza Rivoli
Piazza Robilant
Piazza Vittorio Veneto
Corso Maroncelli

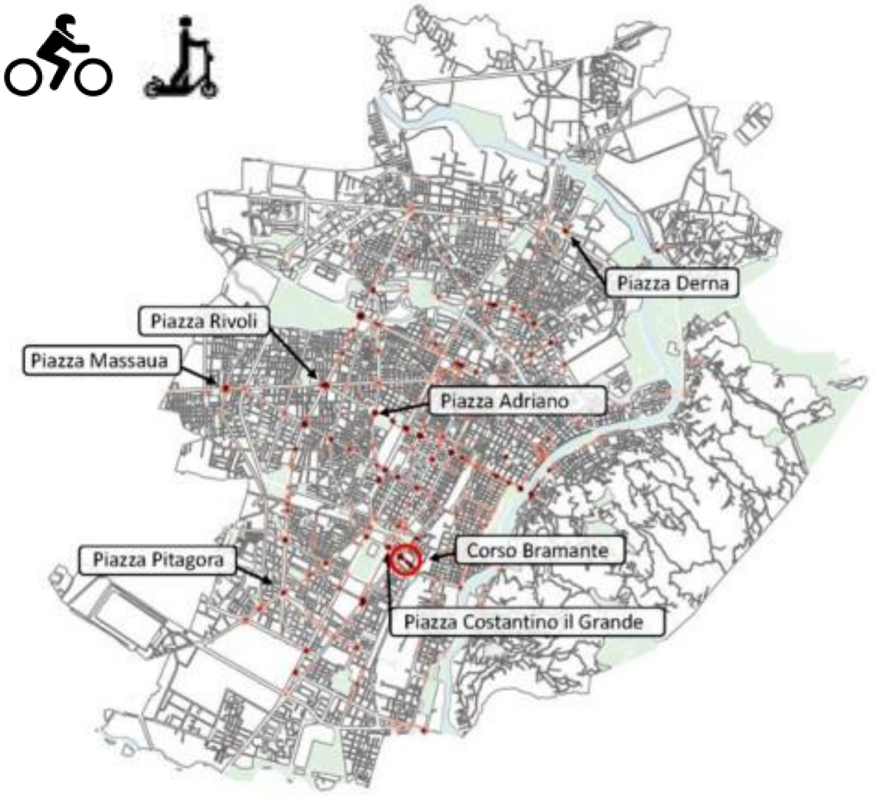
(a)


Piazza Baldissera
Piazza Bernini
Piazza Rivoli
Piazza Statuto

(b)



(c)



(d)

Figure 11. KDE results of (a) pedestrians, (b) bikers, (c) motorcyclists and (d) motorcyclist and moped rider collisions in Turin in the period 2006-2020.

3.1.4 Spatial-temporal analysis of Corso Vittorio Emanuele II

Spatial analysis can reveal false positives and false negatives. False positives are locations that are identified as hazardous in only one of several periods, while false negatives are locations that are not identified as hazardous in one of a long series of periods. To better understand the presence of false positives and negatives, a more detailed analysis was performed along Corso Vittorio Emanuele II.

The cross section of Corso Vittorio Emanuele II consists of a main road with two or more lanes per direction, and two service roads. This is the classic configuration of Turin's avenues. Figure 11 shows all the major intersections in the Corso Vittorio Emanuele II corridor, which are common to both the main and service roads (see Table 3 for names). The main roadway and its intersections are signalized with traffic lights. At the Corso Racconigi intersection there is a left turn lane with a traffic light time dedicated to this manoeuvre. Crosswalks and bicycle lanes are signalized too. In squares, bicycles share the path with pedestrians, while in some segments they circulate in the service road, sharing the lane with vehicles. The traffic rules for cyclists are given through horizontal road markings, but sometimes only vertical signs communicate them to users.

Figure 12 shows intersections with only service lanes (see Table 4 for names). At many of the major intersections, the service roads are equipped with an Advance Space Line (ASL) or Bike Box, which is a space reserved for bicycles only that should be occupied by bicyclists waiting for a green light, in a visible and protected position from vehicles.

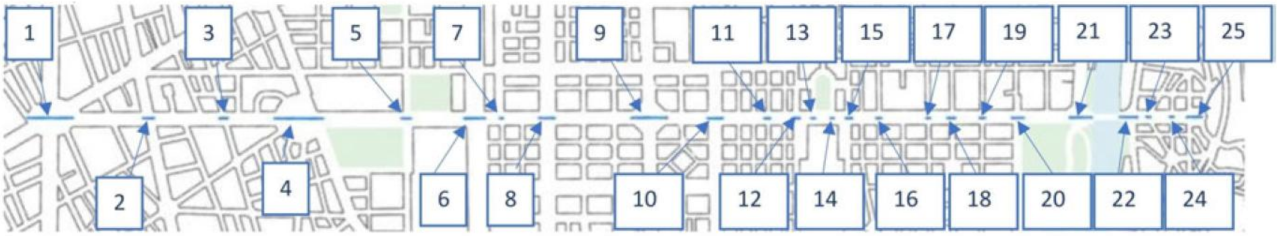


Figure 12. Corso Vittorio Emanuele II intersections of the main and service carriageways.

Table 3. Names of the crossing roads with the main carriageway of Corso Vittorio Emanuele II.

n°	Square or Intersection with	n°	Square or Intersection with
1	Piazza Rivoli	14	Piazza Carlo Felice
2	Corso Racconigi	15	Via Giuseppe Luigi Lagrange
3	Corso Aurelio Saffi	16	Via Carlo Alberto
4	Piazza Adriano	17	Via San Francesco da Paola
5	Via Paolo Borsellino	18	Via Accademia Albertina
6	Corso Inghilterra	19	Via San Massimo
7	Corso Bolzano	20	Corso Massimo D'Azeglio
8	Corso Vinzaglio	21	Corso Cairoli
9	Corso Galileo Ferraris	22	Corso Moncalieri
10	Corso Re Umberto	23	Via Casteggio
11	Via dell'Arsenale	24	Via Cosseria
12	Via Paolo Sacchi	25	Piazza Crimea
13	Piazza Carlo Felice		

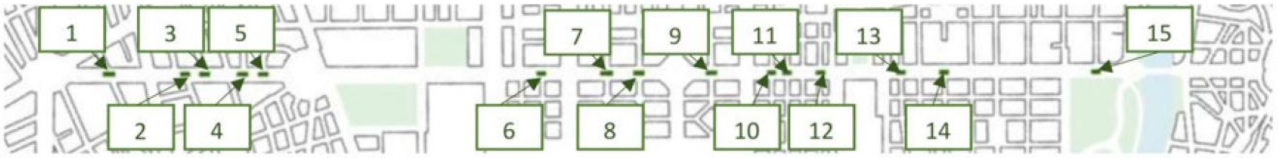


Figure 13. Corso Vittorio Emanuele II intersections of the only service carriageways.

Table 4. Names of the crossing roads with the service carriageway of Corso Vittorio Emanuele II.

n°	Intersection with	n°	Intersection with
1	Via Villar Fioccardo	9	Via Vincenzo Bellini
2	Via Revello	10	Via Giuseppe Parini
3	Via Caprie	11	Via Melchiorre Gioia
4	Via Groscavallo	12	Via Alessandro Volta
5	Via Federico Paolini	13	Via Urbano Rattazzi
6	Via Luigi Colli	14	Via Sant'Anselmo
7	Via Vitaliano Donati	15	Via della Rocca
8	Via Amedeo Avogadro		

The spatial-temporal analysis of the accidental events that occurred during 2006-2020 in the Corso Vittorio Emanuele II corridor is shown in Figure 13. The analysis was performed using a dedicated algorithm in Python code. Collision data were plotted as points in a two-dimensional graph, with the station of the corridor on the abscissae, and the temporal location on the ordinates. A moving window of arbitrary horizontal and vertical size was moved along the two axes, and events falling within it were counted. The height of the window was set equal to one year, with a search step of 3 months. The width of the window was set at 100 m with a search step of 10 m. Clusters were identified when the window detected more events than the threshold set at 3 collisions, and the area was highlighted graphically in yellow. Figure 13 shows the analysis of only those incident events that involved at least one VRU.

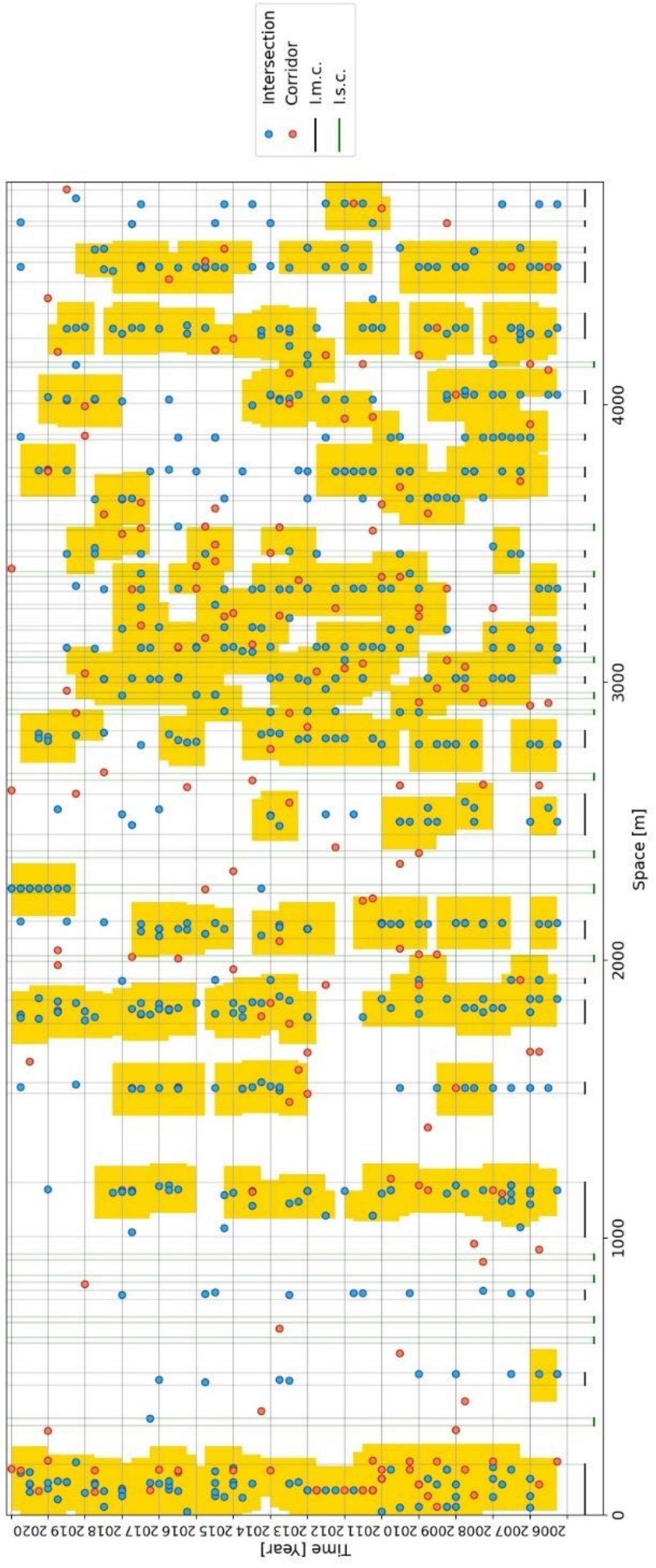


Figure 14. Spatio-temporal analysis results for VRU collisions (Notes. I.m.c. = Intersections of the Main Carriageway, I.s.c. = Intersections of the Service Carriageway only.

The intersections identified as hazardous by the spatial-temporal analysis are those that show a temporal continuity of windows with above-threshold events. Although the density-based methodology identified some of these sites as hazardous, for many intersections there are periods in which the collision frequency was below the threshold. The exceptions are Piazza Rivoli, which is constantly above the threshold, and the intersections between Rivoli and Adriano squares, where no significant accident densities are evident. This uneven distribution of accidental events concerning VRUs is of interest for this study, and the causes that make some intersections of the same corridor safer than others will be carefully evaluated in the next steps of the research.

3.2 Case study 2: Rome

The process adopted by the Roma Tre Research Unit for HRL identification was structured as follows:

1. Preliminary consultation with "Roma Servizi per la Mobilità" and the Mobility Department of the Municipality of Rome;
2. Application of the method described in Section 2.2, Kernel Density Estimation, to the areas identified during the consultation with stakeholders ("Roma Servizi per la Mobilità" and the Mobility Department of the Municipality of Rome);
3. Selection of the site of interest based on the results of KDE and the intrinsic characteristics of the site.

3.2.1 Consultation with Roma Servizi per la Mobilità and the Mobility Department of the Municipality of Rome Capital

Prior to the beginning of experimental activities, consultations were held with several stakeholders including entities, institutions of the Municipality of Rome Capital ("Roma Servizi per la Mobilità" and the "Assessorato-Mobility Department") in order to:

(i) better communicate the objectives of ARCADE project,
(ii) acquire the necessary accident data for analysis
(iii) obtain guidance on identifying the site for detailed field experiments and driving simulation studies.

As a result of these consultations, Roma Servizi per la Mobilità provided accident data for the decade 2011-2020 concerning events involving Vulnerable Road Users (VRUs), and identified two major areas of the city of Rome (Balduina and Colli Aniene neighborhoods), where planned mobility improvement and renovation interventions are scheduled, which will be the focus of subsequent analyses.

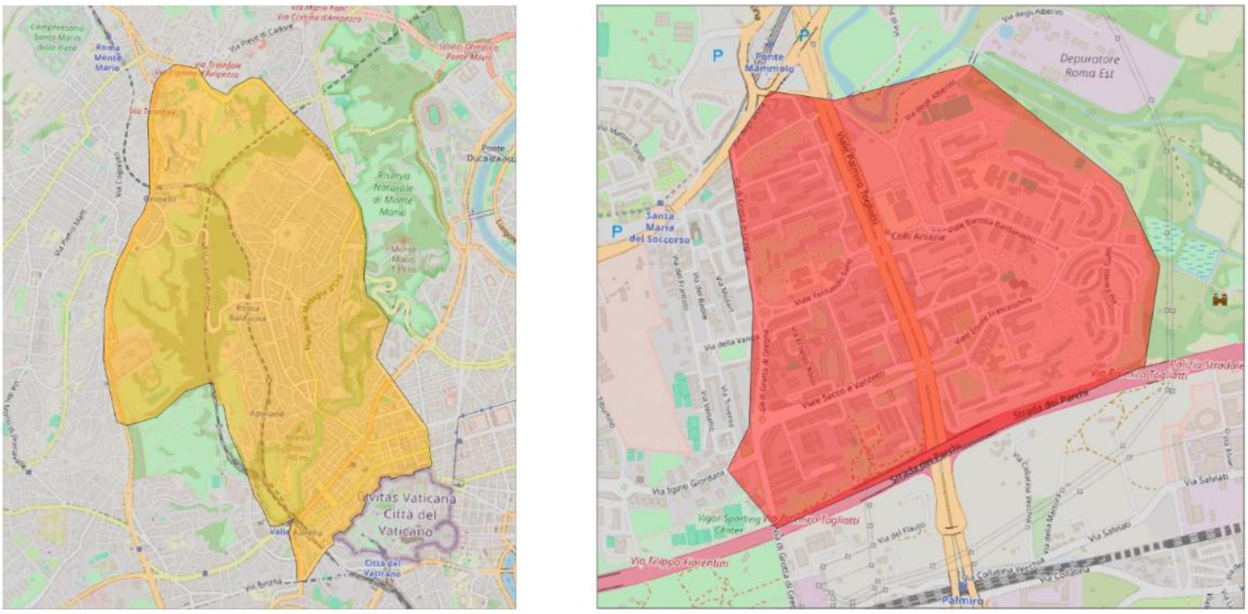


Fig. 14 –Areas of interest: Balduina (left) and Colli Aniene (right)

3.2.2 Application of the method described in Section 2.2: Kernel Density Estimation

With reference to the two identified areas (Balduina and Colli Aniene), the analyses outlined below have been conducted.

3.2.2.1 Descriptive statistics

The two neighbourhoods under analysis, identified following the interaction with the institutional stakeholders, represent well the critical issues detected throughout the city of Rome (RSM, 2021). Such critical issues highlight that users of two-wheeled vehicles (motorcycles and mopeds) and the pedestrians are the road users at greatest risk.

As a case study, the Balduina area in northwest Rome offers a valuable context for examining traffic incidents involving Vulnerable Road Users (VRUs). This area is characterized by a combination of residential and commercial spaces, contributing to diverse traffic patterns and road user interactions. Figure 15 reports the number of accidents involving VRUs in the Balduina area over a ten-year period (2011-2020). The analysis reveals a significant prevalence of motorcycle-related accidents (578), accounting for over 63% of the total VRU incidents. This finding suggests a substantial reliance on motorcycles for local mobility, highlighting the need for more detailed investigations focused on this category of road users.

On the other hand, a significant number of accidents involved pedestrians, totaling 170 and accounting for 18.66% of all cases, which constitutes a substantial category of vulnerable road users (VRUs) in the studied area. This raises notable concerns about pedestrian safety. Moreover, the complete absence of electric scooter accidents and the low incidence of bicycle-related accidents, at just 1.32%, may indicate potential barriers to the adoption of these modes of transportation.

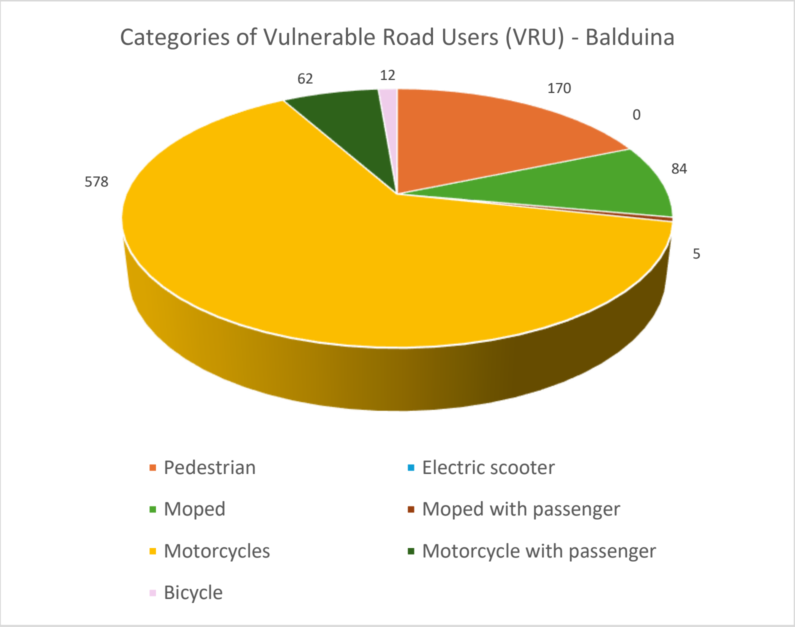


Fig. 15 – Distribution of Incidents of VRU of Balduina

The number of accidents for each VRU category, providing an overview of their representation in the area under study over a ten-year period (2011-2020), is reported in Table 3 and figure 16. The number of pedestrian accidents remains relatively stable throughout the years, fluctuating between a minimum of 11 in 2015 and a maximum of 22 in 2017. The total number of pedestrian accidents over the period is 170. No accidents involving electric scooters are reported for 2020, reflecting the low usage or the absence of recorded incidents.

Table 5. Distribution of accidents of VRU over Balduina, Rome, Italy

Year	Pedestrian	Electric scooter	Motorcycles	Moped	Bicycle
2011	18	0	84	24	0
2012	19	0	70	11	0
2013	18	0	67	12	2
2014	19	0	67	9	2
2015	11	0	59	8	0
2016	15	0	49	4	0
2017	22	0	62	8	3
2018	17	0	63	6	0

2019	12	0	60	5	2
2020	19	0	59	2	3
Total:	**170**	**0**	**640**	**89**	**12**

Motorcycle accidents consistently account for the largest number of incidents each year, peaking at 84 in 2011 and gradually decreasing to 59 by 2020. The overall trend indicates a steady decline in motorcycle accidents (i.e. motorcycles and motorcycles with passenger), with a total of 640 over the period. The number of accidents involving mopeds shows a general downward trend, starting from 24 in 2011 and decreasing to 2 by 2020. The total number of moped accidents is 89. Bicycle-related accidents are sporadic and relatively low, with a total of 12 incidents recorded over the decade. The highest numbers are observed in 2017 and 2020, with 3 incidents each year.

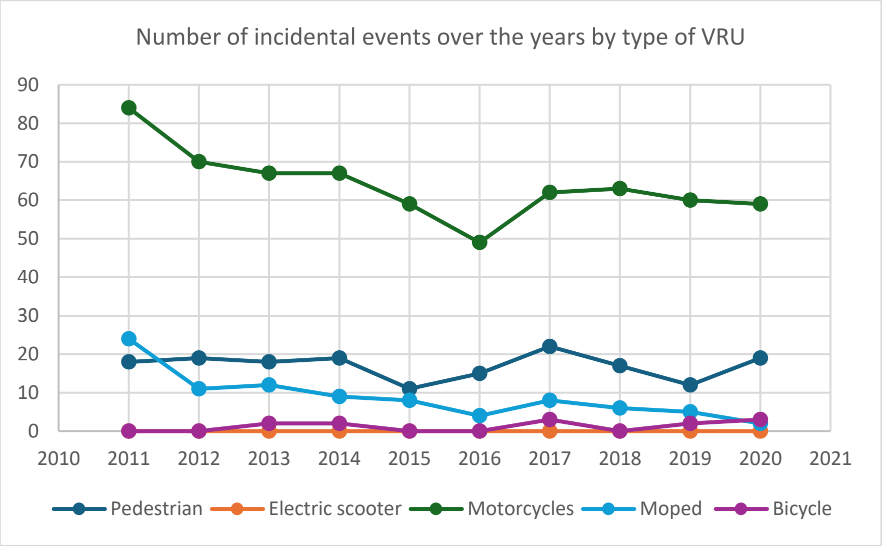


Fig. 16 – Number of accident events over the years by type of VRU – Baludina, Rome

The second detailed analysis focuses on the “Colli Aniene” area in Rome, selected as a case study. This area, located in the eastern part of the city, offers an important context for examining traffic incidents involving Vulnerable Road Users (VRUs), over a ten-year period (2011-2020). Colli Aniene is characterized by a variety of residential areas and industrial zones, contributing to varied traffic dynamics and interactions between different road users. The analysis examines different categories of Vulnerable Road Users (VRUs). The number of accidents for each VRU category is reported and highlighted in Fig. 17. The group with the highest percentage of accidents is motorcycles, accounting for 185 events, corresponding to 67.27% of the total, indicating the predominance of this class among VRUs. Pedestrians follow with 30 (10.91%), while 26 accidents involve motorcycles with passengers, which represent 9.45%. Mopeds account for 8.73%, and bicycles make up 2.91%. Finally, both electric scooters and mopeds with passengers have the lowest percentage, at 0.36%.

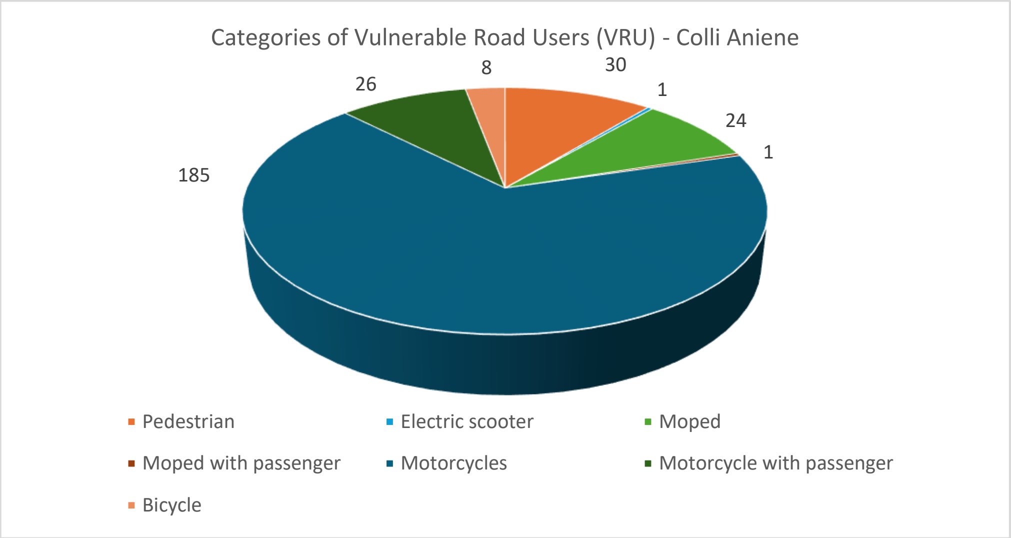


Fig. 17 – Distribution of Incidents of VRU of Colli Aniene

Table 4 and figure 18 present the number of accidents for each each VRU category, providing an overview of their representation in the area under study over a ten-year period (2011-2020). The number of pedestrian accidents shows a declining trend, starting with 5 incidents in 2011 and dropping to 1 in 2015 and 2017, while an increase is detected between 2018-2020. The total amount of pedestrian accidents over the decade is 30. Only one accident involving an electric scooter was recorded in 2016. This minimal presence suggests either low usage or a lack of reported incidents throughout the other years.

Table 4. Distribution of accidents of VRU over Colli Aniene, Rome, Italy

Year	Pedestrian	Electric scooter	Motorcycles	Moped	Bicycle
2011	5	0	32	6	1
2012	2	0	28	0	1
2013	4	0	22	3	1
2014	2	0	22	6	2
2015	1	0	15	2	1
2016	4	1	20	1	1
2017	1	0	16	3	1
2018	4	0	18	1	0
2019	3	0	30	1	0
2020	4	0	8	2	0
Total	**30**	**1**	**211**	**25**	**8**

Motorcycle accidents represent the majority of incidents over the years, with a total of 211. The peak occurs in 2011 with 32 incidents, but there is a noticeable decrease over the years, except in 2019 when 30 accidents were recorded, with the lowest number being 8 in 2020. Moped accidents are relatively low, with a total of 25 incidents over the decade. The data shows some fluctuations, peaking at 6 in 2014 and 3 in 2017, but overall remains at a low level. Bicycle-related accidents are sporadic, totaling only 8 incidents over the ten-year period. The highest number recorded in any single year is 2, which occurs in both 2014 and 2016. The motorcycle accidents are the most prevalent among VRUs in this area, with a significant number over the investigated decade. Pedestrian accidents are reduced, while incidents involving electric scooters, mopeds, and bicycles are relatively few and sporadic.

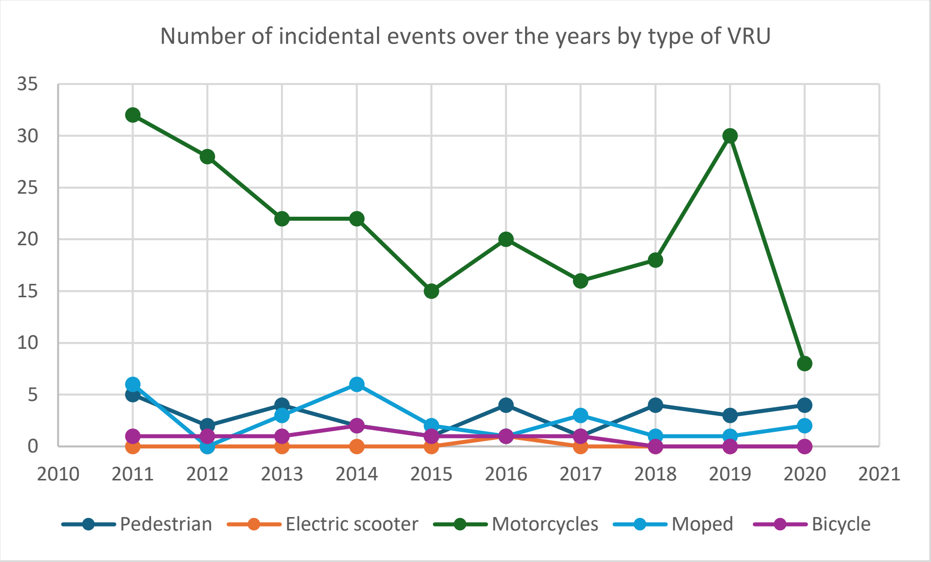


Fig. 18 – Number of accident events over the years by type of VRU – Colli Aniene, Rome

3.2.2.2 Data Acquisition and Processing

This chapter addresses the acquisition and processing of incident data for the period 2011-2020 and the creation of the final database, which is essential for the analysis of interest in this study. The entire process can be summarized in three main phases:

1. Extraction of incidents involving Vulnerable Road Users (VRUs) in Rome within specific areas identified as "area of interest".
2. Geolocation of incidents in a Geographic Information System (GIS).
3. Development of the database for the spatial distribution analysis of incidents.

The analyzed database distinguishes five classes of vulnerable road user types:

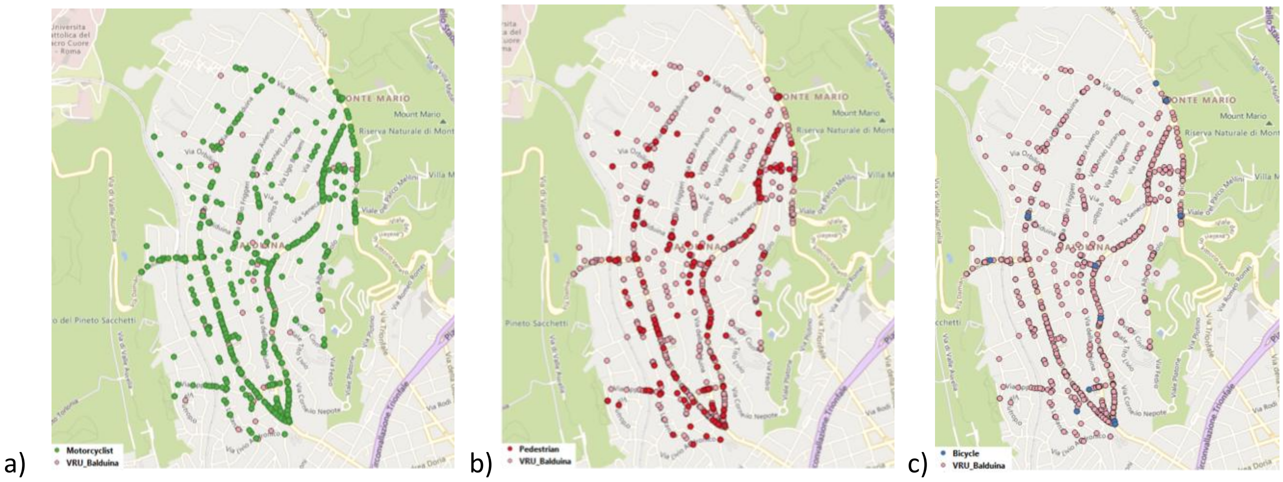
- Pedestrians
- Mopeds

- Motorcycles
- Bicycles
- E-scooters

The incident data for the areas of interest (Balduina and Colli Aniene) were extracted from the main database, which contains data on accidents involving Vulnerable Road Users recorded during the decade 2011-2020 across the entire city of Rome, provided by RSM and imported into the GIS environment. This process generated a computerized database that, in addition to geographic coordinates, enables the immediate visualization of accident information over a reference basemap. The following figure (Figure 19) represents the number of VRUs occurred in Baludina (Fig. 19 a) and Colli Aniene (Fig 19b). The graphical representation offers direct and clear visual feedback on the distribution of incidents involving motorcyclists over the considered decade. An intuitive perspective that can be crucial for road safety decisions and strategies within the study area.

Fig. 19– Study area of interest a) Balduina and b) Colli Aniene and example of an incident (involving the VRU) for the decade 2011-2020

Figure 20 provides an example of GIS-based visualization of accidents involving motorcyclist (green) and pedestrians (red), in relation of the totality of VRUs accidents (pink) which occurred within the study area of Balduina, during the decade 2011 to 2020. Specifically, the GIS-based visualization shows ~~highlighting~~ the frequency of motorcycles (in green in Fig, 20 a), pedestrian incidents depicted in red (Fig. 20 b), and Bicycle (blues) relative to the total number of incidents involving Vulnerable Road Users (VRUs), which are visually distinguished in pink.



a) b) c)

Fig. 20 – Study area of interest Balduina: representations of accidents related to: (a) motorcyclist (green); b) pedestrians (red) and c) cyclists (blue), in comparison to the accidents of VRUs (pink)

An example of the information associated with each accident, which can be directly investigated within a GIS environment, is presented in Figure 21, illustrating the information related to a specific accident.

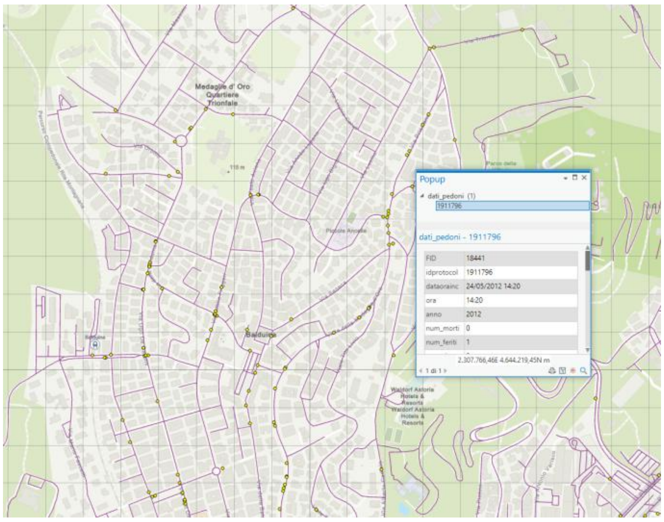


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Fig. 21 –GIS-based Visualization of the Number of Pedestrian Incidents (in yellow) and the attribute values with all the information

3.2.2.3 Kernel Density Estimation and Heatmaps – Density Concentration Maps

The Kernel Density Estimation (KDE) was conducted using the following specifications:

1) Kernel Density Estimation with barriers (constrained to the road network), where distances between events (di), necessary for density determination, are not Euclidean distances but distances measured along the road network, following the shortest-path tree. This approach allows for calculating density values exclusively along the road network where the incident event can actually occur, excluding buildings, green areas, urban parks;
2) a Gaussian distribution has been selected as kernel function K;

3) the value of the bandwidth h was chosen based on a preliminary analysis of sensitivity, that was carried out varying the parameter h among values of 50, 100, and 150 meters. A such analysis, showed that the measure of 100 meters 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 (Bassani et al. 2020).

To conduct density analysis in the urban study zones, surfaces were modeled using external software to create "barrier" entities for Kernel Density Estimation (KDE). In the graph creation, both building structures and barriers were included to accurately represent the road network (fig. 22 a and b). This approach allowed for the analysis of incident distribution, identifying areas with higher concentrations while considering the influence of barriers such as buildings and green spaces on kernel density.

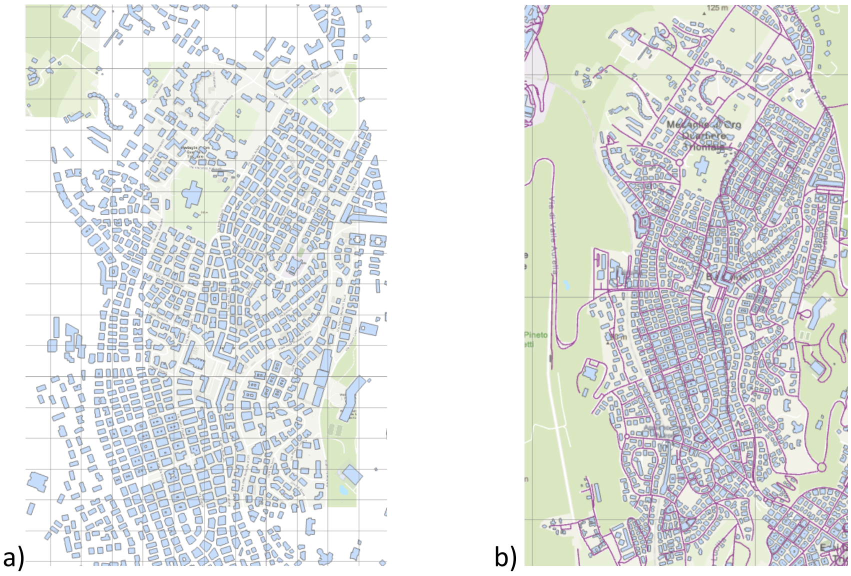


Fig. 22 – a) Creation of barriers (in blue), representing the building areas excluded from the Kernel Density Estimation (KDE) calculation; b) visualization of the road layer where accidents are located

To identify high-risk zones for Vulnerable Road Users (VRUs), an aggregate analysis process was conducted. This methodology involved a comprehensive assessment of incident data involving vulnerable users, aiming to pinpoint particularly critical geographical areas. The aggregate analysis entailed the collection and synthesis of incident data associated with VRUs, including pedestrians, cyclists, and motorcyclists.

The risk classification was established according a statistical criterion, as reported in section 2.2. Specifically, the final interval (characterized by kernel densities exceeding the mean value plus 6 standard deviations: $f(uv) > \mu + 6\sigma$) was chosen/selected to identify hazardous road sites. The analysis conducted has led to the identification of particularly critical areas (black spots or Hazardous Road Locations, HRLs) in the Balduina neighborhood and in the Colli Aniene district, where significant incidents involving Vulnerable Road Users (VRUs) have occurred. Figures 23 and 24 show the output of Kernel Density Estimation (KDE) with barriers for Balduina and Colli Aniene areas.

Fig. 23 - Output of Kernel Density Estimation (KDE) with barriers - Identification of HRL (Balduina)

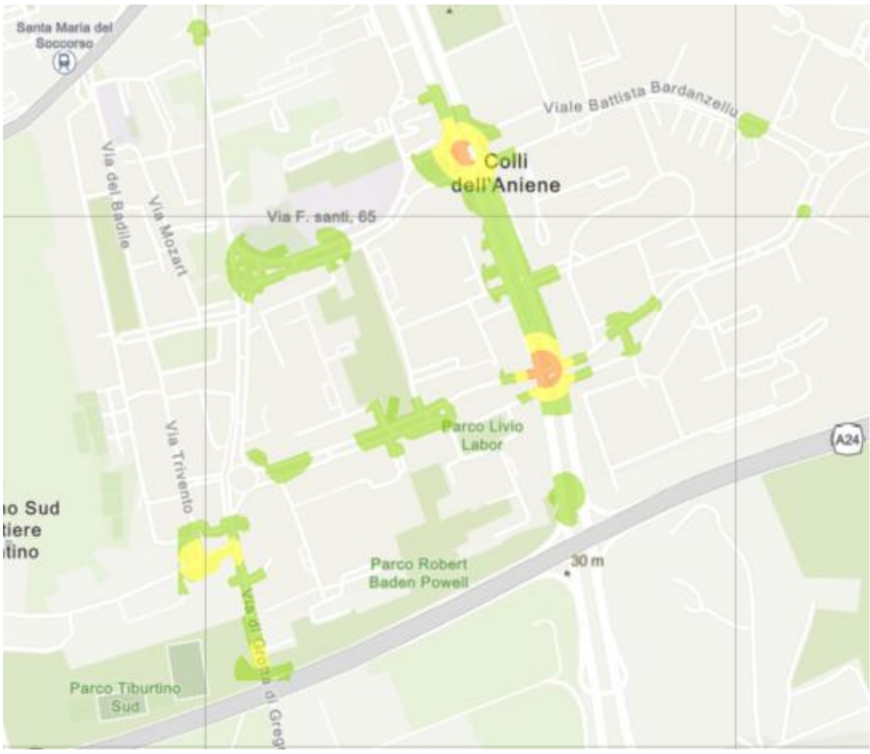


Fig. 24- Output of Kernel Density Estimation (KDE) with barriers - Identification of HRL (Colli Aniene)

3.2.3 Identification of the site of interest based on the KDE results and the intrinsic characteristics of the site.

Among the sites identified as HRL in the two districts of Colli Aniene and Balduina, the intersection between Via delle Medaglie d'Oro and Via Cecilio Stazio in the Balduina district was chosen for subsequent detailed analyses. This site was selected as satisfying the following criteria:

- the site is susceptible to numerous potential measures for reducing the risk to Vulnerable Road Users (VRUs);
- the intersection is unsignalized;
- the possibility of conducting detailed field surveys and accurate driving simulation.

To confirm the criticality of the selected site, a survey was conducted among the citizens of the districts involved in the analyses, from which it emerged that the chosen site is perceived as one of the most dangerous. For this area, in order to provide further insights to refine intervention strategies, concise incident statistics have been determined, relating to the total number of incidents from 2011 to 2020, outcomes of the incidents (uninjured, injured, or fatalities), and types of VRUs involved (e.g., pedestrians, motorcyclists, cyclists). This has helped to better understand the specific dynamics related to the occurrence of these incidents, contributing to guiding the investigations to be conducted in the subsequent phases (field surveys and driving simulator experimentation). The results of the Kernel Density Estimation (KDE) applied to the intersection of interest, highlighting areas with varying concentrations of Vulnerable Road User (VRU) accidents are presented in Figure 25. The figure also includes the geolocation of individual VRU accidents, which are superimposed on the KDE output to provide a spatial representation of accident density.

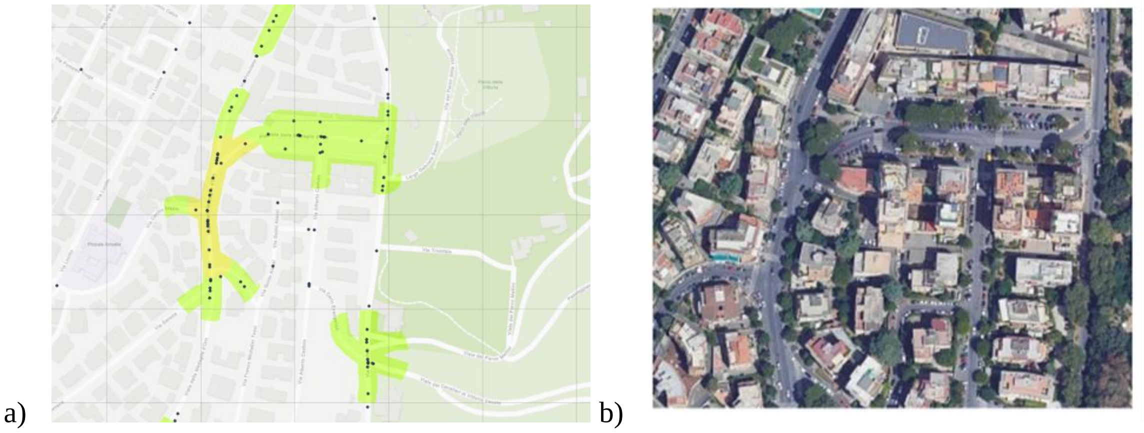
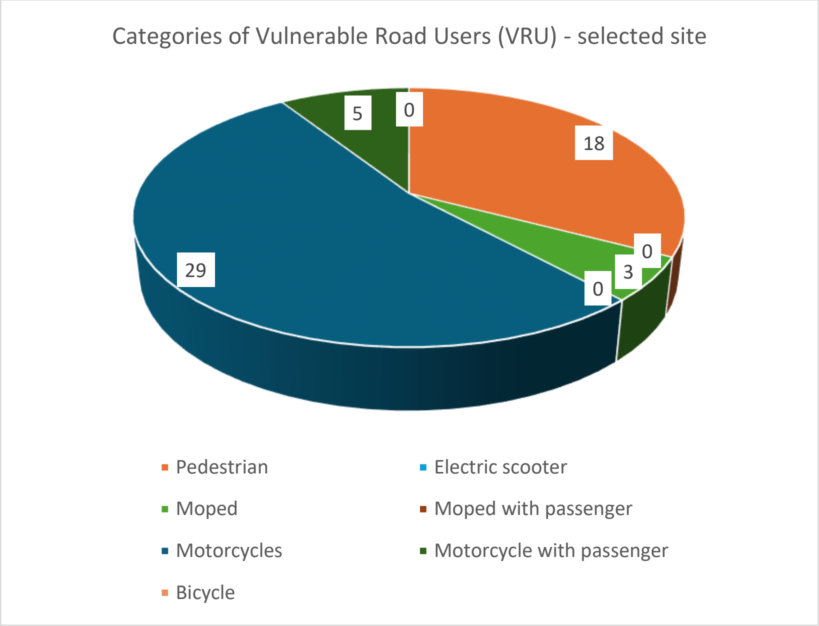


Fig. 25 – Results of the Kernel Density Estimation (KDE) applied to the intersection of interest, along with the visualization of the geolocation of Vulnerable Road User (VRU) accidents b) aerial view of the intersection

The data reveals that 55 incidents involved Vulnerable Road Users (VRUs). Among these, 15 individuals were uninjured, while 40 sustained injuries, with no reported fatalities. An analysis of the types of Vulnerable Road Users (VRUs) involved indicates that motorcyclists constitute the largest group, accounting for 52.73% (29 out of 55) of the accidents. This is followed by pedestrians, who represent 32.73% with 18 incidents. Additionally, 9.09% of the incidents involved motorcyclists with passengers (5 cases), while mopeds were involved in 5.45% of the accidents (3 cases). Notably, there were no incidents reported for electric scooters, or bicycles. The following graph illustrates the number of accident events over the years by type of Vulnerable Road User (VRU).



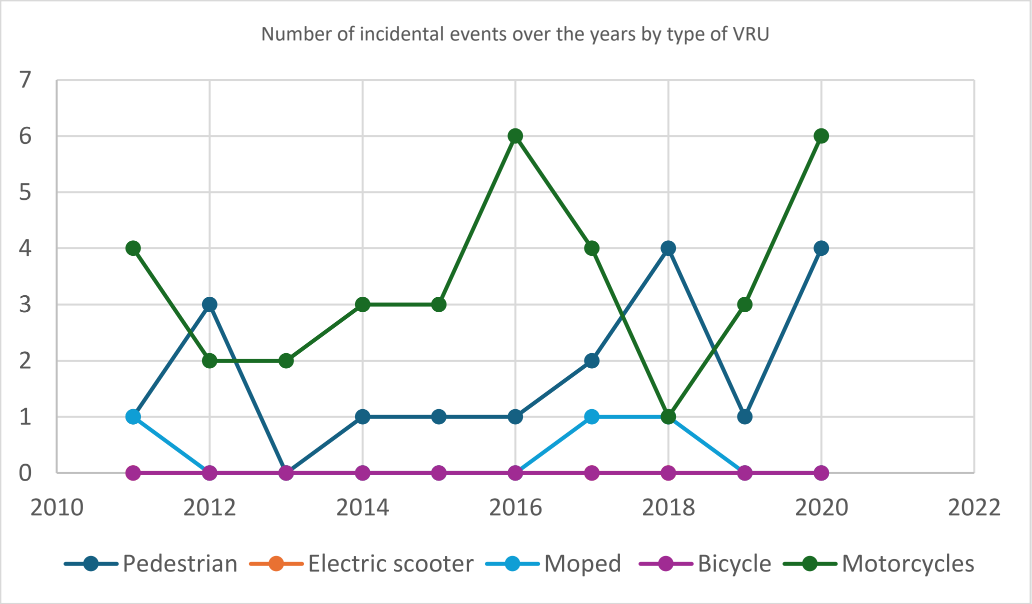


Fig. 26 –Accident data for the selected site in Balduina district

4 Final remarks

4.1 Turin

As the descriptive statistics showed, collisions involving at least one VRU represent 42.5% of the total number of collisions registered in Turin. Moreover, 65.7% of the registered fatalities are among VRUs, with pedestrians being the most affected category. It is also worth noting that the only category that has shown an increasing trend over the years is that of cyclists. It can be concluded that for Turin it is necessary to ensure a higher level of safety for pedestrians and cyclists to promote these components of mobility.

To understand where to act, a spatial analysis was carried out to identify HRLs in the network. The Nearest Neighbour analysis identified a clustered structure of crash events, and the results obtained with KDE for each sub-category of VRUs showed how the main critical points are concentrated in the main corridor intersections. Based on the analyses carried out so far, both for all VRUs and for individual sub-categories there is redundancy of collisions at intersections and segments along Corso Vittorio Emanuele II. For this reason, the research unit of the Politecnico di Torino is interested in developing further analyses along this corridor within the ARCADE project. Over the past ten years, different crash frequencies have emerged depending on the type of intersection. Some of the intersections along the corridor with a low crash frequency can provide insights into the safety countermeasures to be adopted for those with a higher frequency.

4.2 Rome

Following discussions with institutional stakeholders (“Roma Servizi per la Mobilità” and the Mobility Department of the Municipality of Rome), the identification of HRL sites was conducted in two neighborhoods of the city (Colli Aniene and Balduina), where planned mobility improvement and renovation interventions are scheduled.

The accident statistics for these two areas represent well the critical issues detected throughout the city of Rome: the users of two-wheeled vehicles (motorcycles and mopeds) and pedestrians are the road users at greatest risk.

Among the sites that KDE highlighted as critical, a site, located in the Balduina neighborhood, was chosen on the basis of its intrinsic characteristics. The requirements that guided the choice were the following: the site is susceptible to numerous potential measures for reducing the risk to Vulnerable Road Users (VRUs); the intersection is unsignalized; possibility of conducting detailed field surveys and accurate driving simulation. The chosen site was also found to be among the most critical by a survey conducted among the citizens of the district involved in the analyses.

For the decade 2011-2020, the analysis of the types of Vulnerable Road Users (VRUs) involved in accidents indicates that motorcyclists and mopeds constitute the largest group, accounting for 67 % (37 out of 55) of the accidents. This is followed by pedestrians, who represent 33% with 18 incidents. No accidents were reported for bicycles, probably due to the limited use of this mode of mobility in the area of interest.

4.3 Padua

Following discussion with institutional stakeholders (Padua municipality and local traffic police), the identification of HRL sites was mainly conducted based on traffic intensity in the potential HRL and on the number of critical events involving VRUs in each site. No spatial statistical analysis was performed in this case, but the definition of the final HRL site was guided by descriptive statistics on critical events and critical discussion with stakeholders. The selected HRL site (“Gattamelata-Modena”) also allow to reduce the risk of simulation sickness in the CAVE virtual environment, considering the limited number of curves and roundabouts in the simulation.

In proximity of the selected HRL site, a prominent number of critical events in the last decade involved VRUs (89%), with the 20% involving pedestrians, 35% motorcyclists, and 60% cyclists. Notably, the 30% of these accidents involved motorcyclists and cyclists at the same time. The 56% of the reported accidents on this site happened in proximity of road crossings and the intersection. Only 7 events (20%) were reported concurrently to rainy weather. The 38% of the events took place during heavy traffic

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