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Geospatial Analysis of Wildlife–Vehicle Collisions in the Federation of Bosnia and Herzegovina: Identification of High-risk Zones

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ABSTRACT

Wildlife–vehicle collisions (WVCs) represent a growing safety, ecological, and economic challenge, with direct consequences for human lives, material damage, and biodiversity conservation. In the Federation of Bosnia and Herzegovina, systematic analyses that link traffic accidents caused by collisions with wildlife are lacking. This research identifies high-risk locations of WVCs and applies geospatial analysis to the main roads of the Federation of Bosnia and Herzegovina. The analysis is based on official police reports documenting 14,169 traffic accidents between 2021 and 2023, of which 104 cases (0.73%) were classified as animal-related. Although species were not specified in the reports, these accidents predominantly occurred in areas where wildlife crossings are expected, and thus are treated as potential wildlife–vehicle collisions. The results indicate a concentration of WVCs in nine municipalities, with eight critical road segments identified on main roads. Additional analyses explored the relationship between collisions, road infrastructure (bridges, tunnels), and ecological features of habitats (Emerald Network, Natura 2000, Red List of FBiH, IUCN). Based on the findings, it can be concluded that spatially targeted prevention is essential, with priority given to infrastructural measures (wildlife overpasses, fencing, signage) and strategic measures (improved databases, continuous monitoring, and integration into spatial planning). The obtained results provide a foundation for policies that simultaneously enhance traffic safety and contribute to the protection of wildlife populations.

Keywords: Emerald network, geospatial analysis, Natura 2000, prevention measures, risk zones, road infrastructure, traffic accidents, wildlife-vehicle collisions (WVCs)

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INTRODUCTION

Wildlife–vehicle collisions (WVCs) represent an increasingly pressing challenge in the fields of road traffic and biodiversity conservation. Such accidents result in a wide range of consequences – from human casualties and material damage to the decline of protected and endangered species populations and the fragmentation of their habitats. These collisions contribute to population declines, genetic isolation, and habitat fragmentation, with especially severe impacts in biodiversity-rich regions and near protected areas or migration corridors (Quintana et al. 2022, Koju et al. 2025a). Particularly problematic are cases occurring near protected areas and migration corridors, where wildlife–vehicle collisions can pose long-term threats to ecosystem stability.

Data on WVCs represent not only a safety and ecological concern but also a valuable source for monitoring wildlife populations (Lind Hansen et al. 2024). Contemporary research reviews emphasize that the problem of wildlife–vehicle collisions must be approached in a multidisciplinary manner – as a safety, ecological, and socio-economic challenge (Pagany 2020, Balčiauskas et al. 2025). Factors such as road network density, vehicle speed, seasonal patterns, and habitat configuration play a crucial role in determining the likelihood of wildlife–vehicle collisions (Pagany 2020, Laube et al. 2023, Dawson et al. 2025). The resulting economic and ecological consequences include population declines, habitat fragmentation, and substantial societal costs (Su et al. 2023). Integrated, context-specific mitigation is essential to reduce risks for both wildlife and society.

The frequency of wildlife–vehicle collisions is influenced by spatial and ecological factors such as forest proximity, terrain configuration, and seasonal patterns, while the impact of traffic flows and accompanying infrastructure is less straightforward. The highest collision risks occur on roads that pass through or alongside forests and natural habitats, near wildlife movement corridors, on segments with poor visibility and sharp curves, and during periods of increased animal activity (dusk, dawn, migration) (Neumann et al. 2012, Laliberté and St-Laurent 2020, Laube et al. 2023, Bhandari et al. 2024). However, some studies have shown that WVCs are not determined solely by these factors but also by temporal patterns (Vrkljan et al. 2020). It has been established that these accidents occur most frequently at dusk and during night-time. These results highlight the need to incorporate spatial, ecological, traffic-related, and temporal dimensions of risk into analyses and preventive planning. At the same time, increasing emphasis is placed on integrating nature conservation into transportation infrastructure planning, as well as on employing ICT technologies (GIS, AI, sensor systems) and involving citizens in monitoring to develop sustainable and locally adapted prevention measures.

Recommended measures for preventing and reducing wildlife–vehicle collisions include the installation of physical barriers, the construction of wildlife crossings, dynamic signage, and targeted warnings at the identified hotspots (Litvaitis and Tash 2008, Fedorca et al. 2021, Sevigny et al. 2021, Kučas et al. 2023). Such measures have proven effective in practice as they guide the movement of wildlife and reduce conflicts with traffic, while simultaneously supporting the preservation of migration corridors. Their implementation requires a combination of strategic planning and localized interventions to ensure long-term road safety and biodiversity conservation.

In the Federation of Bosnia and Herzegovina, no comprehensive study has yet integrated the spatial distribution of WVCs with road infrastructure characteristics and ecologically significant areas. A further challenge is that official traffic accident records rarely indicate whether the animals involved are wild or domestic species, nor do they specify the exact species. This significantly limits the ability to assess the true ecological impact of these events. The lack of an integrated analytical framework hampers the identification of critical road segments, the evaluation of risk patterns, and the development of targeted mitigation measures that would simultaneously improve traffic safety and support biodiversity conservation. Nevertheless, the spatial context of collisions can provide a reasonable basis for inference: accidents occurring in remote forested, mountainous, or agricultural areas, far from settlements, farms, or livestock-grazing zones, are far more likely to involve wild species than domestic animals.

This study aims to identify high-risk locations of WVCs and to conduct a geospatial analysis along the main roads of the Federation of Bosnia and Herzegovina. Also, we offer guidance for enhancing road safety and biodiversity conservation. Accordingly, the study seeks to address the following research questions:

- What are the spatial characteristics of the distribution of wildlife–vehicle collisions on the main roads in the Federation of Bosnia and Herzegovina? This question targets both macro- and micro-spatial patterns of WVCs occurrence, including the exact locations of collisions in relation to the road network and surrounding habitats.
- Do zones of high spatial concentration of WVCs ("risk zones") exist, and how can they be objectively ranked? The goal is to identify critical points and road segments that require priority intervention.
- To what extent do identified high-risk locations overlap with ecologically significant areas, such as protected habitats? This question links the safety and ecological dimensions of the problem.
- Which preventive measures can be considered most effective for the identified locations? The focus is on the practical implications of the results, i.e., the selection of infrastructural and strategic measures that can reduce risk.

In this way, the research connects the safety dimension of road traffic with nature conservation, providing results relevant both for transport planners and for natural resource managers.

MATERIAL AND METHODS

Geospatial analysis provides an effective tool for identifying locations with an increased risk of wildlife–vehicle collisions. Geospatial methods such as Kernel Density Estimation (KDE), logistic regression, and environmental factor-based modelling have proven effective in identifying and predicting wildlife–vehicle collision "hotspots" along road networks

(Visintin et al. 2016, Ha and Shilling 2018, Fedorca et al. 2021, Laube et al. 2023). These methods enable the mapping of high-risk areas by considering factors such as proximity to forests, vegetation type, road curvature, traffic noise (as an indicator of traffic flow), visibility, and seasonal wildlife migrations. Accurate mapping of such zones allows for the implementation of targeted and effective measures aimed at reducing WVCs and preserving biodiversity.

The focus of this study is the main road network of the Federation of Bosnia and Herzegovina, a region characterised by forested areas, karst fields, and river valleys where transport corridors frequently intersect natural wildlife habitats. These environmental and infrastructural conditions create favourable settings for wildlife–vehicle collisions and therefore justify the need for detailed geospatial risk analysis. Although the primary geospatial analysis is based on road segments and administrative units, the methodological framework also recognizes the importance of micro-location and temporal characteristics of wildlife–vehicle collisions. The available accident records contain spatial coordinates with varying degrees of accuracy, allowing for preliminary identification of micro-clusters along specific road segments, but not always enabling a uniform level of detail required for full micro-scale modelling. Similarly, the time of day is recorded inconsistently across cantonal datasets, which limits the possibility of temporal pattern analysis. Nevertheless, both dimensions—micro-location and temporal factors—are acknowledged as critical determinants of collision risk and will be incorporated in future research phases as more complete and standardized datasets become available.

This research is based on a case study approach, employing geospatial analysis combined with elements of descriptive and evaluative analysis. The analysis was based on a structured set of spatial, infrastructural, ecological, and accident-related variables extracted from multiple datasets. The descriptive approach provided a detailed insight into the spatial distribution of wildlife–vehicle collisions, while the evaluative approach was used to identify and assess high-risk locations and to define recommendations for preventive measures. Such methodological framework contributes to the development of recommendations that simultaneously enhance traffic safety and support biodiversity conservation.

The analysis was based on a set of spatial, infrastructural, ecological, and accident-related variables. Key variables included the geographic coordinates of collisions, administrative locations, and road sections. Additional infrastructural and traffic variables, such as road segment length, distance between neighbouring collision points (Euclidean and network-based), proximity to tunnels and bridges, average annual daily traffic (AADT), and average vehicle speed, were also incorporated. Ecological variables included the distance to Natura 2000 and Emerald Network areas, land-use/land-cover categories, and proximity to habitats of protected species. Together, these variables enabled the identification, spatial clustering, and ranking of high-risk locations.

Therefore, multiple data sources were used in this research, including:

- **Traffic accident data:** For the period 2021–2023, official records were obtained from the cantonal ministries of interior in the Federation of BiH. A total of 14,169 accidents were analyzed, of which 104 (0.73%) were recorded as involving animals (Ministarstva unutrašnjih poslova kantona u Federaciji BiH 2024). Although wildlife–vehicle collisions are recorded in official police reports, the species involved are not systematically documented. In the available accident records no information was provided on the type of wildlife involved, which prevents species-specific analysis.
- **Road infrastructure and traffic data:** The data were collected from JP Ceste FBiH (JP Autoceste Federacije BiH 2024; JP Ceste Federacije BiH 2024a, 2024b) and the OpenStreetMap (OSM) database. These datasets included the network of main roads, average annual daily traffic (AADT), average vehicle speed, as well as the locations of bridges and tunnels.
- **Ecological data**: Included spatial databases of Natura 2000 sites in the Federation of BiH (Federalno ministarstvo okoliša i turizma 2024a), Emerald Network of BiH (Federalno ministarstvo okoliša i turizma 2024b), the IUCN Red List of Threatened Species (International Union for Conservation of Nature (IUCN) 2024) and the Red List of Fauna of the Federation of BiH (Federalno ministarstvo okoliša i turizma 2021). The ecological datasets used in this study provide habitat- and area-level information, but not detailed species-level distributions for game animals. They were therefore applied to assess habitat overlapping rather than to analyse specific wildlife species.

Although the applied geospatial and evaluative approaches provide valuable insights into the identification of high-risk zones, certain limitations need to be acknowledged. The primary constraint is the lack of detailed data on the specific species of animals involved in collisions, which restricts the possibility of assessing the impact on individual populations. Additionally, inconsistencies in traffic accident reporting systems may lead to underreporting or misclassification of WVCs. These limitations imply that the results should be interpreted with caution and complemented by field surveys, ecological monitoring, and continuous improvements in accident reporting systems.

For the purposes of this analysis, a multilayer GIS database was developed in the QGIS environment. The database included administrative boundaries, road network and associated infrastructure, recorded WVCs locations, as well as ecologically significant habitats and migration corridors. OpenStreetMap (OSM) layers and Google Satellite orthophotos were used as cartographic basemaps, enabling precise georeferencing of the data. The geospatial analysis was conducted by combining various GIS techniques and spatial operations. Spatial overlay methods (Intersection, Spatial Join) were applied to examine the relationships between the road network, collision sites, and protected species' habitats. In addition, buffer zone analysis (distance of collisions from bridges and tunnels) was performed to identify spatial relations, along with a geospatial analysis of collisions across administrative units.

In the context of this research, the term "risk zone" was introduced and defined as a spatially limited road segment where three or more wildlife–vehicle collisions were recorded within a three-year period, with the distance between two neighboring collisions not exceeding 3 km. This fixed-segment thresholding follows approaches commonly used in previous research, where a minimum of two to three collision events is considered sufficient to indicate a non-random spatial pattern (Malo et al. 2004, Manap et al. 2021, Geremew 2024). Using a lower threshold (e.g., two collisions per segment) would result in a larger number of smaller clusters with reduced analytical relevance, while a higher threshold (e.g., four or five collisions) would omit several meaningful hotspots and underestimate risk. Thus, the chosen threshold ensures a balance between sensitivity and analytical robustness. For each identified zone, a collision index per kilometer (number of collisions / zone length) was calculated, allowing comparisons between zones of different length and the determination of relative risk intensity. This definition of risk zones provides a consistent and objective basis for ranking locations that require priority preventive measures.

The identification of high-risk zones in this study was based on spatial proximity (Euclidean distance) between collision points. This approach was selected because relying solely on linear distance along the road axis would produce inconsistent and potentially misleading results. Many road segments in the study area have highly irregular geometry due to terrain constraints (e.g., steep gradients, tight curves, and serpentine alignments). On such roads, the chainage-based distance between two collision points can be several times greater than their actual separation in geographic space, while on straight road segments the opposite is true. This discrepancy would distort the comparison of collision clustering across road types and undermine the comparability of results. Additionally, wildlife movement occurs in the landscape surrounding the road corridor rather than strictly along the roadway itself. WVCs happen when animals cross or temporarily use the road surface, meaning that spatial (Euclidean) proximity more accurately reflects ecological reality than chainage-based distance. For these reasons, a spatial clustering approach was considered the most appropriate method for identifying high-risk zones under the available data conditions. Future studies that have access to chainage-based crash coordinates could implement a moving-window analysis along the road alignment to further refine hotspot detection.

The obtained results were interpreted in the context of road infrastructure and ecological characteristics of the area. In this way, the methodology enabled the identification of: critical sections of main roads, municipalities and cantons with the highest concentration of collisions, and areas where high-risk zones overlap with ecologically significant habitats. This methodological approach allowed for the precise identification of high-risk zones and the development of scientifically grounded recommendations for appropriate measures. The defined risk zones represent a foundation for planning infrastructural measures (eco-ducts, protective fencing, signage) and strategic measures (database improvement, monitoring, integration into spatial planning) aimed at reducing conflicts between traffic and wildlife.

RESULTS

The analysis of wildlife–vehicle collisions was conducted at three complementary levels: administrative boundaries (cantons and municipalities), segments of main roads, and micro-locations identified as spatially limited segments within those road sections. This multi-layered approach provides a comprehensive perspective on the problem, from broader regional distribution patterns, through infrastructural specificities, to the precise identification of points with the highest risk intensity.

To ensure more accurate identification of high-risk locations and to account for differences in segment lengths, the term "risk zone" was introduced. This concept enables the extraction of spatial clusters of collisions and their comparison through the collision index per kilometer, thereby establishing a consistent basis for ranking zones and precisely mapping critical road sections.

Table 1 presents an overview of the number of wildlife–vehicle collisions by municipalities and segments of the main roads, while Table 2 provides data on the identified risk zones. In addition to the number of collisions, supplementary data are included that can serve for more detailed analysis and correlations with factors such as average traffic intensity, vehicle speed, and proximity to protected areas. These values were treated as contextual indicators of general traffic conditions rather than as independent predictors, and were used primarily to aid the interpretation of high-frequency collision segments. In this context, they contributed to the quantitative framework for analysing the distribution of wildlife–vehicle collisions across administrative units and critical road sections, as well as their relationship with infrastructural features and nearby ecologically significant areas. In this way, the results of the geospatial analysis enable the identification and ranking of priority locations where infrastructural and strategic preventive measures need to be planned and implemented.

However, due to the absence of species-level information and detailed temporal attributes, statistical correlations would not yield reliable or generalizable conclusions. For this reason, the analysis conducted in this study is primarily spatial and descriptive, focusing on the identification of risk zones rather than on establishing causal statistical relationships. Future research based on larger datasets and more comprehensive variables could enable the application of advanced statistical and predictive modelling. Additionally, although the police reports included basic accident-severity categories, these were not incorporated into the ranking of segments, as the primary objective of this study is to examine spatial clustering and collision density. Nevertheless, integrating severity-weighted indicators could further enhance the prioritization of high-risk segments in future analyses.

Distribution of WVCs in Terms of Administrative Boundaries

In the analyzed period 2021–2023, a total of 14,169 traffic accidents were recorded, of which 104 (0.73%) involved animals. Although the share of WVCs in overall statistics is relatively low, their spatial concentration in certain administrative units indicates localized risk factors (e.g., proximity to forested areas, transition zones between urban and natural habitats, and road sections located within protected areas or intersecting potential migration corridors).

At the cantonal level, the analysis shows that Zenica-Doboj Canton (39) and Canton 10 (38) reported the highest number of recorded accidents. Central Bosnia Canton (10), Una-Sana

Table 1 High-risk road sections in the Federation of Bosnia and Herzegovina (2021–2023).

Munici-pality	Number of WVCs	Road	Section	Section length (km)	Number of WVCs on the section	Number of WVCs per km	Average traffic intensity	Average vehicle speed	Distance from pro-tected area (km)
Livno	27	M15	Livno 4 – Suica	23.5	27	1.149	1598	73	1.6
Zenica	21	M17	Lasva – Biljesevo	4.6	9	1.957	6570	86	0
		M17	Zepce 11 – Nemila	21.3	1	0.047	11870	61	0
		M17	Nemila – Lasva 0	29.1	11	0.378	10489	85	0
Maglaj	16	M17	Karuse – Zepce 11	35.6	16	0.449	11784	64	0
Kupres	11	M16	Kupres 1 – Suica	20.2	10	0.495	2543	93	0
		M16	Bugojno 2 – Kupres 1	22.3	1	0.045	4723	61	0
Travnik	10	M5	Donji Vakuf 1 – Turbe	26.4	3	0.114	2960	75	1.6
		M5	Turbe – Nevic Polje	12.3	7	0.569	13618	58	1
Sanski most	9	M15	Sanski Most 1 – Kamicak	12.5	9	0.720	3348	63	0
Kladanj	5	M18	Zivinice 1 – Vitalj (Stupari)	30.1	3	0.100	5518	66	3.4
		M18	Vitalj – Olovo	20.2	2	0.099	4451	61	2.2
Orašje	3	M14.2	Bosanski Samac – Orasje	18.2	1	0.055	2851	75	0
		M1.8	Granica BH/HR (Zupanja) – Loncari	11.2	2	0.179	5323	75	0
Tešanj	2	M4	Teslic (Barici) – Karuse	22.8	2	0.088	17079	107	2.7

Table 2 High-risk zones on the observed roads in the Federation of Bosnia and Herzegovina (2021–2023).

Munic-ipality	Road	Section	High-risk zone (HZR)	Length of the HZR (km)	Number of WVCs in HZR	Number of WVCs in HZR per km	Average traffic intensity	Average vehicle speed	Distance from pro-tected area (km)
Livno	M15	Livno 4 – Suica	M15-ZR1	6.3	27	4.3	1598	73	1.6
Zenica	M17	Lasva – Biljesevo	M17-ZR1	3.2	9	2.8	6570	86	0
	M17	Zepce 11 – Nemila	/	/	/	/	/	/	/
	M17	Nemila – Lasva 0	M17-ZR2	5.3	6	1.1	13247	58	0
	M17	Nemila – Lasva 0	M17-ZR3	0.3	3	10	7731	58	0
Maglaj	M17	Karuse – Zepce 11	M17-ZR1	3.2	9	2.8	11784	64	0
			M17-ZR2	1.2	6	5	17079	107	0
Kupres	M16	Kupres 1 – Suica	M16-ZR1	2.9	5	1.7	2543	93	0
	M16	Bugojno 2 – Kupres 1	M16-ZR2	2	4	2	4723	61	0
Travnik	M5	Donji Vakuf 1 – Turbe	/	/	/	/	/	/	/
	M5	Turbe – Nevic Polje	M5-ZR1	3.5	7	2	13618	58	1
Sanski most	M15	Sanski Most 1 – Kamicak	M15-ZR2	9	8	0.9	3348	63	0
Kladanj	M18	Zivinice 1 – Vitalj (Stupari)	M18-ZR1	2.4	3	1.25	5518	66	3.4
	M18	Vitalj – Olovo	/	/	/	/	/	/	/
Orašje	M14.2	Bosanski Samac – Orasje	/	/	/	/	/	/	/
	M1.8	Granica BH/HR (Zupanja) – Loncari	/	/	/	/	/	/	/
Tešanj	M4	Teslic (Barici) – Karuse	/	/	/	/	/	/	/

Canton (9), and Tuzla Canton (5) also recorded a number of accidents, while in Posavina Canton 3 accidents were reported. On the other hand, in Bosnian-Podrinje Canton, Herzegovina-Neretva Canton, Sarajevo Canton, and West Herzegovina Canton, no accidents were recorded according to the analyzed data. However, it cannot be stated with certainty that no such accidents occurred, as it is possible that in police reports used for this analysis, accidents involving animals were recorded in a manner that did not explicitly specify their causes.

Given the predominantly rural, forested, and mountainous character of the locations where these accidents occurred, it is reasonable to assume that the majority of animal-related collisions likely involved wildlife rather than domestic species. Although species-level data are absent from the police reports, the spatial context provides a strong indication that most incidents fall within the category of WVCs. This assumption is also supported by previous research. Studies from Nepal and Switzerland show that rural, forested, and mountainous regions are consistently identified as WVC hotspots, with the vast majority of incidents involving wild rather than domestic animals (Laube et al. 2023, Koju et al. 2025a). Furthermore, numerous studies indicate that the proximity to forests, low building density, and limited agricultural or urban land use are strong predictors that collisions in such areas predominantly involve wildlife, even when species-level information is missing from official reports (Malo et al. 2004, Pagany 2020). Police and governmental datasets from several countries similarly confirm that in regions with low human density and extensive natural habitats, the species most frequently involved in collisions are wild mammals, particularly large herbivores and carnivores (Malo et al. 2004, Vrkljan et al. 2020). For example, in Spain wild boar and roe deer accounted for 79% of all WVCs in mountainous provinces (Sáenz-de-Santa-María and Tellería 2015).

The overview of WVCs by cantons enables a comparison of the relative burden among these administrative units (Figure 1). This representation clearly highlights the zones with elevated accident intensity.

Additionally, the cartographic representation of accident distribution within municipal administrative boundaries (Figure 2) confirms that most recorded accidents occur in peripheral zones of municipalities and forested areas. Notably, the most frequent accidents are concentrated on sections passing through forest–mountain regions, as well as those linking major urban centers with rural zones. This pattern is consistent with expectations: as traffic intensity intersects with the increased likelihood of wildlife crossings, the risk of WVCs rises accordingly.

Therefore, the administrative breakdown of results has two key implications:

– it enables the prioritization of cantons and municipalities where risk is statistically and spatially more pronounced, and
– it provides a cartographic foundation for moving toward the analysis of main road sections (Section 3.2) and the ecological dimension (Section 3.3), where high-risk zones are more precisely located and linked to infrastructural features.

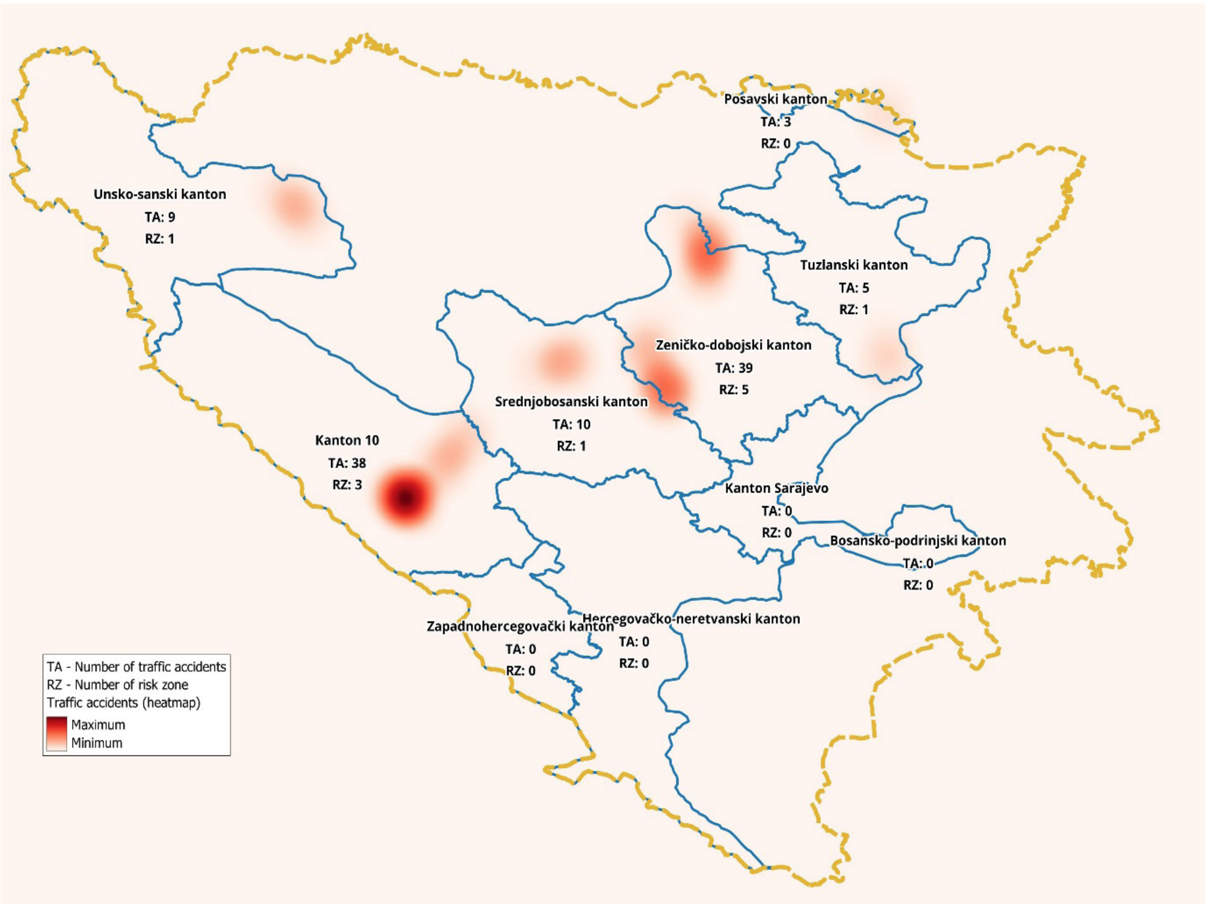

Figure 1 Spatial distribution of WVCs.

Overall, this analysis is valuable for strategic guidance (e.g., selecting cantons/municipalities for priority action), while operational implementation requires a focus on specific road sections and micro-locations.

Distribution of WVCs along Main Road Sections

A detailed spatial analysis was conducted at the level of main road sections in the Federation of Bosnia and Herzegovina, with the aim of identifying those stretches where wildlife–vehicle collisions occur most frequently. This approach enables a transition from the broader administrative scale (cantons and municipalities) to the operational level of the road network, where critical points and high-risk zones can be precisely located.

In total, 104 accidents involving animals were recorded across 17 road sections. The sections with the highest number of accidents were M15 Livno 4 – Šuica (27 accidents), M16 Kupres 1 – Šuica (10 accidents), M17 Karuše – Žepče 11 (16 accidents), M17 Lašva – Bilješevo (9 accidents), and M15 Sanski Most 1 – Kamičak (8 accidents). Data analysis shows that the highest concentration of accidents was registered on the M17 corridor, with 35 accidents, while a significant number was also recorded on the M15 corridor with 27 accidents, noting that these accidents were clustered within a single risk zone (densely distributed within a short stretch). Other sections with higher frequencies included M16 and M5, with 10 accidents each, and another stretch of M15, with 9 accidents. Smaller numbers of collisions were recorded on the M18 (4), M1.8 (2), M14.2 (1), M19.2 (1), M4 (2), and M5 (2) corridors. These findings indicate that certain sections, particularly M17 and M15, represent critical high-risk areas that warrant further analysis and the introduction of targeted road safety measures.

In addition to the above-mentioned findings, the distribution of wildlife–vehicle collisions was analyzed in two complementary dimensions:

1. Euclidean (straight-line) distance between collisions, and
2. Network (road) distance along the actual road infrastructure between adjacent collisions.

This dual approach makes it possible to distinguish between accidents that appear "visually close" in straight-line terms and those that are operationally relevant for traffic management when assessed through the road network. In this way, road sections requiring targeted interventions can be more accurately identified.

Although the distribution of WVCs was examined using Euclidean and network distances, no inferential statistical tests were applied. This is primarily due to the relatively small number of recorded collisions and the uneven distribution of events across road sections, which limits the reliability of correlation-based or regression-based analyses. Instead, the study relies on quantitative spatial metrics such as the accident-per-kilometer index, cluster proximity, and density-based identification of risk zones. This approach provides a robust basis for detecting spatial patterns despite the limited sample size. These are widely used and validated methods for analyzing WVCs because the metrics allow

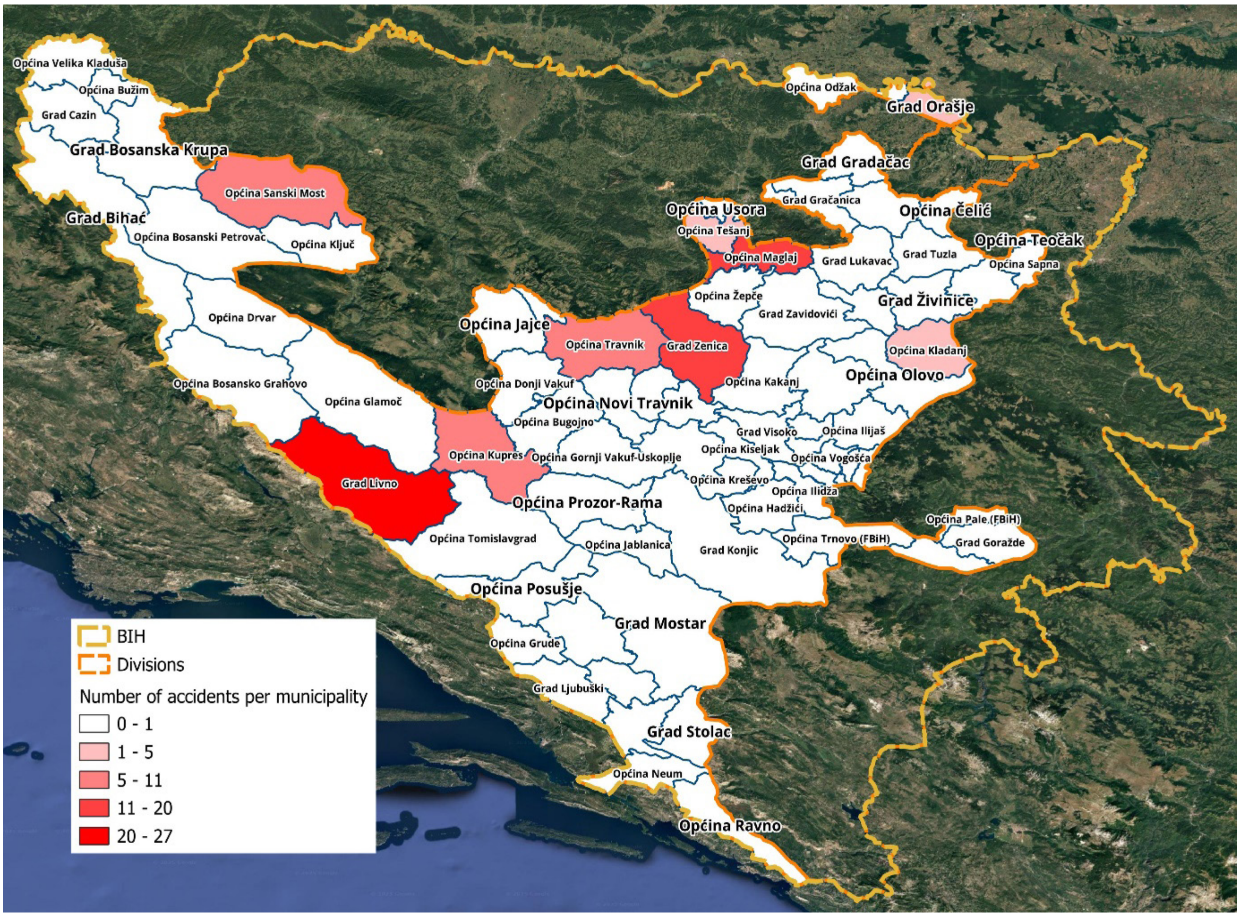

Figure 2 The number of traffic WVCs by municipality.

researchers to pinpoint collision hotspots, assess spatial clustering, and prioritize areas for mitigation, even when the dataset is not large (Morelle et al. 2013, Laube et al. 2023, Koju et al. 2025a).

The results indicate that collisions are unevenly distributed along the main road network, with clear concentrations on certain sections. Figure 3 illustrates one example of collision distribution in the area of Zenica, while equivalent cartographic representations have been prepared for all other identified locations and are available upon request. The most critical sections were identified based on the number of recorded collisions and the calculated accident index per kilometer, enabling valid comparisons across sections of varying lengths. Table 1 and Table 2 present the quantitative overview of results.

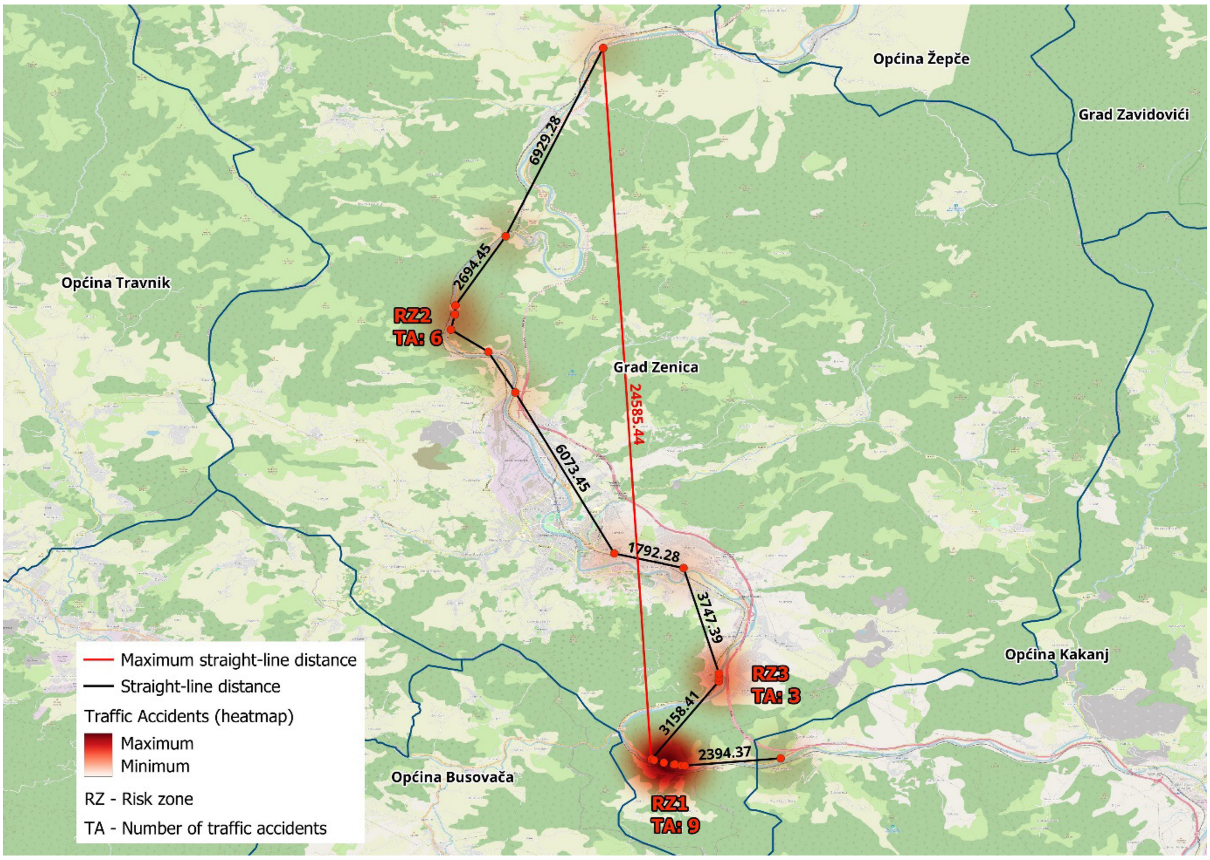

Figure 3 Spatial distribution of traffic WVCs in the area of the City of Zenica.

In addition to the spatial distribution of WVCs, a correlation was carried out with the locations of tunnels and bridges (Figure 4) based on the assumption of their multiple significance in the context of both biodiversity conservation and traffic safety improvement. Bridges and tunnels represent structurally specific segments of road infrastructure that may influence wildlife movement, but their effects are context-dependent and cannot be generalized. By identifying collisions in their vicinity, it is possible to highlight locations that, through relatively minimal interventions, could serve as priority sites for protective measures, such as installing warning signage and guiding fences to channel animal movements, or constructing dedicated crossing structures (ecoducts). Moreover, analyzing these locations helps pinpoint unsafe road segments, where terrain configuration and limited visibility further increase collision risks. Ultimately, these insights contribute to improved spatial planning and the integration of nature conservation principles into transport infrastructure development, thereby ensuring a more sustainable coexistence between humans and wildlife.

The analysis of accidents within a 1 km radius of tunnels identified a total of four WVCs, while no accidents were recorded within a 500 m buffer zone. The highest number of accidents occurred near the Sikola II, Maglaj, and Lješnica tunnels (two in total), while one accident each was recorded near the Kupreška vrata – Koprivnica and Vranduk II tunnels. These findings suggest that the highest risks are not located immediately at tunnel entrances, but rather along access roads or transitional open sections where animals are more likely to attempt crossing. This pattern shows that tunnels rarely function as collision hotspots; instead, they often act as barriers that prevent wildlife from accessing the roadway or as structures that inadvertently facilitate safe movement beneath the road. Therefore, tunnels themselves should not be considered priority locations for mitigation, whereas the surrounding open sections may require closer examination. This is consistent with findings from other studies, which confirm that tunnels and underpasses are generally not collision hotspots (Gilhooly et al. 2019; Koju et al. 2025a, 2025b). Those studies show that such structures typically function either as barriers that prevent wildlife from accessing the road surface or as safe crossing points that enable animals to move beneath the roadway. As a result, these features tend to reduce, rather than increase, the likelihood of WVCs at the tunnel location itself.

All bridges analyzed in this study are conventional road

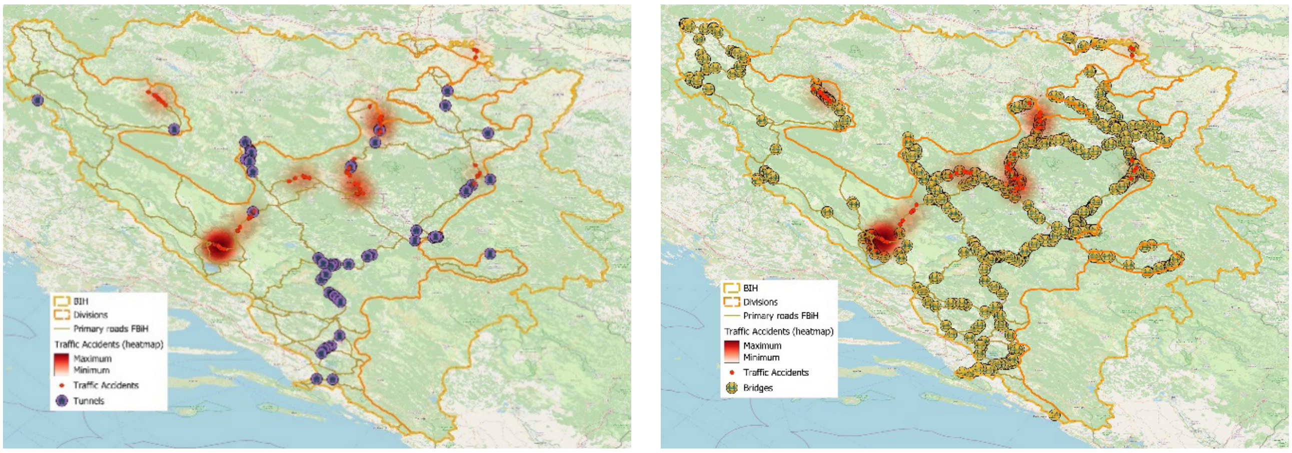

Figure 4 Correlation between accidents and road infrastructure: a) tunnels, b) bridges.

bridges located on the main road network of the Federation of Bosnia and Herzegovina. Within a 500 m buffer around bridges, 17 wildlife–vehicle collisions were recorded, while extending the buffer to 1 km increased this number to 37, indicating that bridge surroundings may function as elevated-risk areas. The highest concentrations were observed near river crossings such as the Sana River (Vrhpolje), the Mošulja and Drinjača streams (Vitalj), and several other single-incident locations. These patterns align with ecological expectations: bridges frequently coincide with river corridors and valley systems that naturally guide wildlife movement. In many cases, bridges are relatively narrow structures without sufficient underpass space for secure wildlife passage, which results in animals crossing the road near the bridges. Consequently, bridge vicinity can become conflict hotspots where topography, watercourses, and road infrastructure intersect. They can create unpredictable risk zones, especially if not designed with wildlife movement in mind (Paemelaere et al. 2023).

Also, bridges are frequently constructed in places where roads cross watercourses or valleys, which are also natural wildlife movement corridors. The surrounding topography and presence of water attract wildlife, while the bridge itself may funnel animal movement toward the road, especially if natural crossing points are limited elsewhere. This convergence increases the likelihood of wildlife attempting to cross the roads near bridges, making these areas potential conflict hotspots (Koju et al. 2025a, Medrano-Vizcaíno et al. 2023). By contrast, tunnels often facilitate safe subterranean movement and help maintain connectivity for terrestrial animals. Overall, the findings suggest that risk does not arise from the bridge structures themselves, but from the ecological–infrastructural interface surrounding them. These transition zones warrant closer examination in future research and represent priority locations for targeted mitigation measures.

The findings presented here do not imply that bridges or tunnels inherently restrict wildlife movement. Instead, they emphasize the need for broader, data-driven research to clarify how various types of road infrastructure interact with wildlife movement patterns and collision risks. Although this study identified noticeable clusters of wildlife–vehicle collisions near several bridge locations, no statistical tests were performed to determine whether these concentrations differ significantly from adjacent road segments. Therefore, these observations should be interpreted as descriptive spatial patterns rather than conclusive evidence of elevated risk. Future research should incorporate spatial statistical analyses to verify these relationships and assess whether bridges, approach zones, or associated river corridors consistently influence collision frequency.

Ecological Context of the Analyzed WVCs

The ecological context of WVCs is of particular importance because it links the safety dimension of road transport with the conservation of biodiversity and natural habitats. Accordingly, the analysis focused on identifying overlaps between accident locations and ecologically significant areas, including protected zones and habitats of species listed under international and national protection frameworks.

A considerable number of main road sections in the Federation of BiH pass through ecosystems of both international and national importance for biodiversity conservation. At the same time, these areas are also zones where the likelihood of wildlife–vehicle collisions is elevated, since road networks intersect with natural migration routes. The results indicate that a significant share of recorded accidents occurs in the immediate vicinity of areas designated within the Natura 2000 network (Figure 5).

The analysis of accidents within 500 and 1000 meters of areas covered by the Natura 2000 network shows that the highest concentration was recorded near the Bosna River, along the M17 main road in the municipality of Zenica, where 31 accidents occurred within the 500 m zone, and 33 accidents within the 1000 m zone. This area clearly dominates the overall values (41 out of 47 accidents), while other protected areas, such as Kupresko polje, Raduša, and Čapljansko polje, show significantly fewer accidents, usually single cases. These results confirm that riverine and alluvial habitats, particularly those running parallel to major transport corridors, are spatially the most sensitive and represent priorities for future planning of preventive measures.

The analysis of the spatial overlap between accidents and habitats of species listed on the Red List of the Federation of BiH and the IUCN Red List shows that, for most species, the greatest vulnerability of Natura 2000 habitats is found in the areas of Kupres and Sanski Most, where frequent WVCs zones overlap with ecologically significant habitats (e.g., Natura 2000 and Emerald areas). Table 3 presents more detailed results of

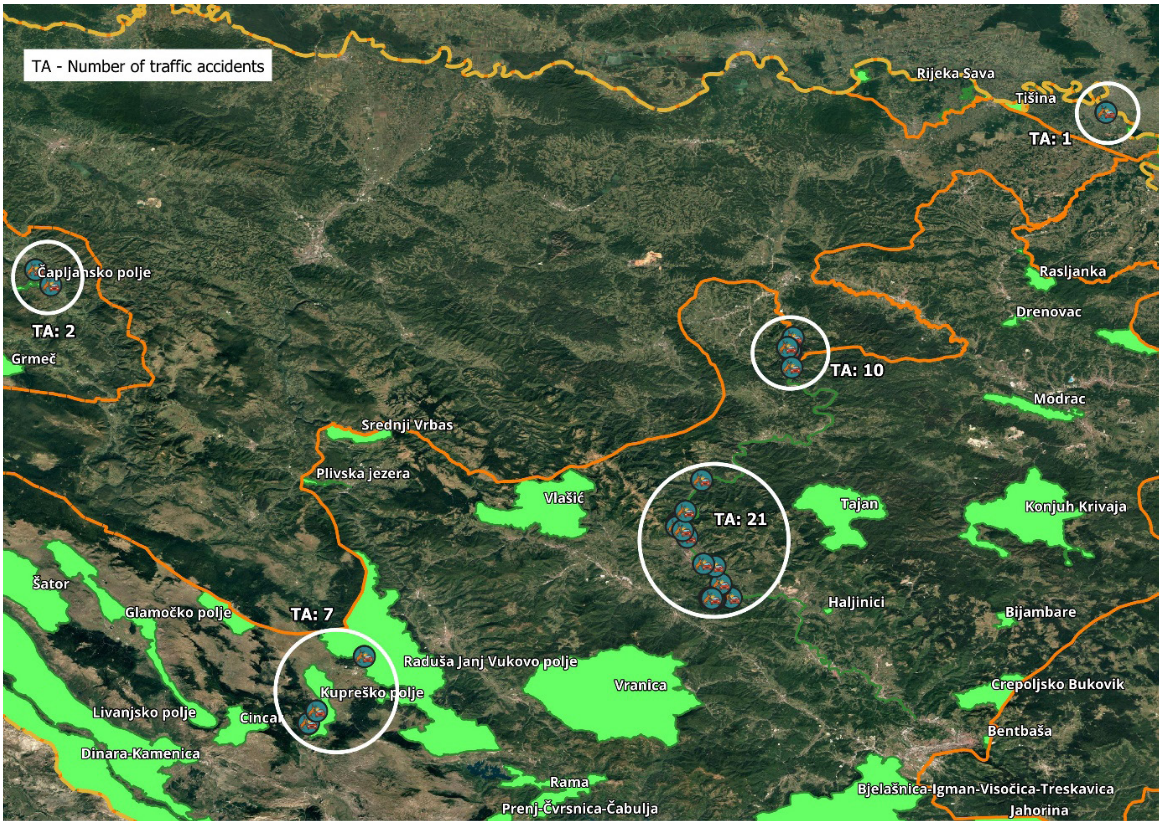

Figure 5 WVCs within 500 meters of Natura 2000 habitats.

Table 3 Characteristics of WVCs in relation to protected areas under the Natura 2000 network.

Road	Section	Length of road section (km)	Municipality	Number of WVCs on the section	Nearest protected area	Distance of the section from the protected area (km)	Area of the protected area (km^2)
M14.2	Bosanski Samac – Orasje	18.222	Orašje	1	Tišina	0	4.195392451
M5	Donji Vakuf 1 – Turbe	26.42	Travnik	3	Vlašić	1.6	136.6875737
M5	Turbe – Nevic Polje	12.3	Travnik	6	Vlašić	1.2	136.6875737
M18	Vitalj – Olovo	20.224	Kladanj	2	Konjuh Krivaja	2.2	167.7815925
M17	Lasva – Biljesevo	4.627	Zenica	9	Rijeka Bosna	0	12.81222171
M16	Kupres 1 – Suica	20.238	Kupres	10	Kupreško polje	0	41.47728505
M15	Livno 4 – Suica	23.533	Livno	27	Livanjsko polje	1.6	359.0018189
M17	Zepce 11 – Nemila	21.345	Zenica	1	Rijeka Bosna	0	12.81222171
M16	Bugojno 2 – Kupres 1	22.307	Kupres	1	Raduša Janj Vukovo polje	0	326.7882715
M17	Nemila – Lasva 0	29.143	Zenica	6	Rijeka Bosna	0	12.81222171
M15	Sanski Most 1 – Kamicak	12.546	Sanski most	9	Čapljansko polje	0	7.262826338
M17	Karuse – Zepce 11	35.588	Maglaj	16	Rijeka Bosna	0	12.81222171
M17	Nemila – Lasva 0	29.143	Zenica	5	Rijeka Bosna	0	12.81222171
M18	Zivinice 1 – Vitalj (Stupari)	30.073	Kladanj	3	Konjuh Krivaja	3.4	167.7815925
M4	Teslic (Barici) – Karuse	22.847	Tešanj	2	Rijeka Bosna	2.7	12.81222171
M5	Turbe – Nevic Polje	12.3	Travnik	1	Vlašić	1	136.6875737
M1.8	Granica BH/HR (Zupanja) – Loncari	11.169	Orašje	2	Rijeka Sava	0	33.02678625

the overlap analysis of WVCs on individual road sections in relation to their distance from Natura 20w00 sites. These findings confirm that those areas are high-risk zones where roads intersect with natural habitats and potential animal migration routes. This pattern has also been confirmed in other studies. For example, in a 12-year study conducted in a Greek Natura 2000 wetland, 78% of all recorded roadkills occurred within the protected area itself, with proximity to water bodies and high traffic volume significantly increasing the risk of collisions (Kouris et al. 2024). Research highlights the need for urgent mitigation in these zones, recommending ecological corridors, wildlife crossings, and targeted interventions to maintain connectivity and reduce animal fatalities.

The analysis of WVCs distribution by landform types shows that the highest number of accidents occurred in heterogeneous agricultural areas, with a total of 43 recorded cases. These areas represent a mosaic of different agricultural activities and are often situated in transitional zones between settlements and natural habitats, which makes them particularly risky in the context of WVCs. Table 4 presents the landform categories where WVCs were recorded. These results provide a valuable basis for future research and the development of new correlations, not only from the perspective of road infrastructure and habitats but also in the context of broader ecological and spatial factors.

Table 4 Landform types in which WVCs were recorded.

Type of Area	Description	Number of Accidents
High-density residential areas	Densely populated urban areas with many buildings and very little greenery	13
Industrial and commercial areas	Zones of industry, commerce, warehouses, and transport infrastructure	2
Arable land (cropland)	Areas used for crop cultivation – fields, farmlands, and gardens	1
Pastures	Grass-covered areas used for livestock grazing	17
Heterogeneous agricultural areas	A mixture of different agricultural activities within one area	43
Agricultural and natural areas	Areas where agriculture intertwines with natural elements	11
Deciduous forests	Forests with broadleaf tree species, such as beech and oak	6
Coniferous forests	Forests dominated by coniferous species, such as pine and fir	1
Mixed forests	A combination of deciduous and coniferous trees	3
Natural grasslands	Untilled grasslands with natural vegetation	2
Inland waters (rivers, lakes)	Areas covered by freshwater – rivers, lakes, reservoirs	5
Sum		104

ANALYSIS AND DISCUSSION

The obtained results clearly indicate that WVCs in the Federation of Bosnia and Herzegovina have a spatially specific character and that risk is not evenly distributed either across administrative units or along the road network. The analysis by cantons and municipalities (Section 3.1) showed that certain administrative areas, particularly those located in the central part of the Federation of BiH, recorded a significantly higher number of WVCs. This finding confirms that spatial patterns are not random, but rather arise from a combination of factors such as traffic flow intensity, proximity to natural habitats, and terrain configuration. The findings of this study are consistent with the results reported in previous research. Some studies have shown that higher traffic volume is consistently associated with increased WVC risk, particularly on road sections characterized by higher vehicle speeds and wider lanes (Pagany 2020, Laube et al. 2023, Koju et al. 2025a). Other research has demonstrated that WVC hotspots frequently occur where roads intersect or run adjacent to forests, agricultural land, meadows, and water sources, which are all landscape features that attract or support wildlife and thereby elevate collision likelihood (Galinskaitė et al. 2022, Su et al. 2023, Koju et al. 2025a). Furthermore, clustering analyses in the literature confirm that WVCs are rarely random events. Instead, they tend to concentrate at specific hotspot locations that correspond with local landscape structure and road characteristics (Bíl et al. 2019, Park et al. 2021, Laube et al. 2023)

A detailed analysis at the level of main roads (Section 3.2) enabled a more precise identification of critical sections that are particularly burdened by this type of WVCs. Eight sections were identified as high-risk, with a significant number of accidents recorded in the immediate vicinity of bridges and tunnels. These findings confirm that infrastructural "bottlenecks" increase the likelihood of wildlife–vehicle conflicts, which is consistent with the results from other European studies reporting similar concentrations of collisions near structural elements and road passages through mountainous terrain. For example, the research by Fedorca et al. (2021) showed that narrow road sections, concrete embankments, and areas with limited wildlife permeability force animals to cross roads at specific points, thereby concentrating both animal movement and vehicle flow. The same study found that vegetation proximity and reduced visibility in the vicinity of such bottlenecks further elevate collision risk by limiting driver reaction time and increasing the probability of wildlife presence. Additionally, previous studies indicate that WVCs often cluster near road signs and bridges, likely because these features coincide with areas of high wildlife activity or reduced driver vigilance (Koju et al. 2025a).

The ecological aspect (Section 3.3) further emphasized the dual vulnerability of high-risk locations – on the one hand, traffic safety, and on the other, biodiversity conservation. Critical road segments often run directly adjacent to ecologically significant zones, increasing the likelihood of collisions with wildlife. This habitat network is of particular importance because it includes ecologically valuable and sensitive areas such as wetlands, river corridors, mountain ranges, and karst fields, which also serve as natural migration routes for wildlife. The results show that a large number of WVCs occur in the proximity or within areas included in the Natura 2000 and Emerald networks. Previous research has likewise reached similar conclusions. For example, studies have shown that roads frequently bisect or run along the edges of Natura 2000 and Emerald Network areas, thereby increasing the likelihood of WVCs due to the high density of wildlife and the ecological importance of these protected habitats (Fedorca et al. 2021). Such spatial overlap contributes to elevated wildlife mortality and undermines the functional connectivity of conservation networks (Helldin 2019). Moreover, even protected areas are not immune to WVCs. High traffic volumes, particularly during tourist seasons, and roads situated along valley bottoms or adjacent to suitable habitats within the protected zones have been shown to further increase collision risks (Fedorca et al. 2021).

In this study, particularly notable is the Bosna River, where on the road section through Zenica more than 40 WVCs were recorded within a 1000 m buffer zone, making it the most burdened natural corridor in the Federation of BiH. Additionally, karst fields (Livanjsko, Duvanjsko, Glamočko, Kupreško) and mountain areas (Prenj, Čvrsnica, Bjelašnica, Igman, Jahorina) confirm that the road network spatially overlaps with the most ecologically valuable zones. Areas such as Livanjsko polje, Duvanjsko polje, Glamočko polje, and Hutovo Blato stand out due to the presence of multiple road sections intersecting these ecosystems. Livanjsko polje is included in both Natura 2000 and Emerald datasets, confirming its status as one of the most sensitive ecosystems in the Federation of BiH. In addition to karst fields, a significant number of sections are linked to river corridors (Bosna, Sava, Una, Rama, Prača). Mountain areas such as Prenj, Čvrsnica, Čabulja, Bjelašnica, Igman, and Jahorina further demonstrate that road infrastructure often overlaps spatially with high-value ecological zones.

The analysis results revealed that certain main roads are particularly prominent in terms of spatial conflict. For instance, the M6.1 section crosses several Natura 2000 and Emerald habitats (Livanjsko polje, Duvanjsko polje, Grabovica Mountain, Dinara–Kamenica, Uilica–Grahovo polje), clearly identifying it as the most sensitive road segment from an ecological perspective. Similarly, the M17 network passes through multiple river and mountain habitats (Bosna River, Sava River, Hutovo Blato, Prenj–Čvrsnica–Čabulja), while parts of the M5 network intersect ecological complexes such as Grmeč, Pliva Lakes, and the Prača Canyon.

Therefore, it can be concluded that road sections located within Natura 2000 and Emerald areas exhibit dual sensitivity – both in terms of traffic safety and the conservation of natural resources. These findings highlight the urgent need to integrate road infrastructure planning with ecological databases and biodiversity conservation strategies. Identifying critical points where WVCs overlap with sensitive habitats enables targeted implementation of preventive measures, such as constructing wildlife overpasses and underpasses, installing protective fencing, and deploying dynamic signage. Preventive measures should be prioritized at these locations, combining infrastructural solutions with strategic approaches that embed ecological criteria into spatial planning and traffic safety policies.

In summary, the analysis of the ecological dimension confirms that high-risk locations are not only a matter of driver safety but also represent a serious threat to the conservation of wildlife populations in the Federation of Bosnia and Herzegovina. The integration of ecological criteria into road network planning and management is therefore essential in order to establish a balance between traffic safety and the protection of natural resources. The most critical road sections were identified precisely in areas that traverse or lie adjacent to Natura 2000 and Emerald sites while simultaneously recording multiple WVCs. This underscores the fact that ecological and safety aspects are inseparable and must be considered in an integrated manner when planning preventive measures.

When all findings are taken together, three key patterns clearly emerge:

1. **Regional concentration** – a higher number of WVCs is observed in the central parts of the Federation of BiH, particularly in certain municipalities and cantons, indicating a combination of traffic intensity and spatial configuration.
2. **Infrastructural factors** – specific terrain configurations, especially the proximity of bridges, represent zones of elevated risk.
3. **Ecological sensitivity** – Natura 2000 and Emerald areas overlap with the most heavily burdened road sections, simultaneously threatening traffic safety and the conservation of wildlife populations.

The limitations of this research stem from the fact that traffic accident records usually do not specify the species involved in the accidents. This makes it difficult to analyze the impact on specific populations, since conclusions can only be based on assumptions. For example, it would be possible to conduct a more detailed analysis of the habitats and migration corridors of certain wildlife species and establish correlations with identified risk zones and WVCs locations. One such case is the population of wild horses in the Livno karst plateau, north of Livno, which can reasonably be assumed to account for a large share of accidents in this area (identified as the highest-risk zone). Nevertheless, the lack of species-specific data does not diminish the validity of the spatial risk zone analysis. The applied methodological framework, identifying risk zones through spatial clustering of accidents, provides a reliable foundation for future research and the planning of preventive measures.

Overall, the spatial risk patterns in the Federation of BiH are consistent with European trends, but the karst fields and the Bosna River corridor represent unique local specificities, highlighting the need for tailored preventive measures. The discussion of these results underscores that spatially targeted prevention is the only effective way to reduce the number of wildlife–vehicle collisions. Integrating geospatial analysis into spatial planning, developing specific protection plans for Natura 2000 and Emerald areas, and implementing infrastructural measures (e.g., ecoducts, underpasses, protective fencing) along with strategic measures (improving databases, systematic monitoring, driver education) represent a necessary course of action. This confirms that synergy between the transport sector and nature conservation is of crucial importance for long-term sustainability and safety in the Federation of Bosnia and Herzegovina.

STRATEGIES FOR REDUCING WVCs RISK

Based on the conducted analysis, it can be concluded that spatially targeted approaches are essential for effectively reducing the number of wildlife–vehicle collisions. While the following section presents general strategic and infrastructural recommendations, it is crucial to emphasize that each identified high-risk location requires a localized approach and the adaptation of measures to its specific ecological, traffic, and spatial conditions.

Strategic measures provide a systemic framework and planning approach through which the issue of wildlife–vehicle collisions is integrated into spatial planning, transport policy, and institutional activities. These include actions such as the development of national and regional databases, monitoring of migration corridors, the adoption of legal and sublegal acts, as well as the education for drivers and local communities. Their particular importance lies in their potential to shape long-term policies and road infrastructure development plans, thereby creating the conditions for a lasting reduction of conflicts between traffic and the natural environment.

Strategic recommendations for the prevention and reduction of wildlife–vehicle collisions include:

- developing strategic documents and plans based on the identified high-risk locations;
- improving the system for collecting traffic accident data, with particular emphasis on recording the species of animals involved (WVCs);
- creating integrated databases that link traffic, ecological, and spatial information;
- implementing continuous monitoring of high-risk locations using GIS tools and dynamic risk indicators;
- incorporating biodiversity protection criteria and wildlife migration corridors into spatial planning and road construction/modernization projects;
- raising awareness and educating road users about risks and ways to reduce the likelihood of collisions.

Infrastructure measures involve concrete physical interventions on roads that directly reduce the risk of wildlife–vehicle collisions. These include solutions such as wildlife overpasses (ecoducts), underpasses, protective fencing, specialized signage, and dynamic warning systems. Their role is twofold; on the one hand, they enhance road user safety, and on the other, they preserve the functional connectivity of natural habitats by reducing ecosystem fragmentation. The importance of infrastructure measures is particularly evident on critical sections of main roads with the highest number of WVCs, as they provide a direct and measurable effect in lowering incident rates.

Infrastructure recommendations for the prevention and reduction of wildlife–vehicle collisions include:

- installing protective fences along high-frequency collision segments, combined with controlled wildlife passages;
- constructing and modernizing ecological crossings (ecoducts, underpasses, wildlife bridges) at priority locations;
- introducing both dynamic and static traffic signage to warn drivers of high-risk zones;
- adjusting speed regimes and implementing speed-reduction measures on critical road sections;
- using new technologies, such as detection systems and smart signage, to provide timely driver warnings;
- installing adequate lighting on critical road sections to improve visibility and reduce risks during night-time driving;
- enhancing visibility on critical locations by clearing and maintaining roadside vegetation, as well as implementing additional infrastructural measures to ensure sufficient sight distance on both sides of the road.

In general, the proposed measures should be viewed as a framework providing both strategic and infrastructural directions for action. However, their implementation must be locally adapted, since specific high-risk locations differ in terms of traffic load, terrain configuration, dominant habitat types, and wildlife migration patterns. Only by combining general guidelines with site-specific solutions can a long-term, sustainable reduction of risk be achieved, while simultaneously enhancing traffic safety and contributing to biodiversity conservation.

CONCLUSION AND FUTURE RESEARCH

The results of the conducted analysis revealed that wildlife–vehicle collisions (WVCs) in the Federation of Bosnia and Herzegovina follow distinct spatial patterns, with risk unevenly distributed across administrative units and segments of the road network. Critical sections of national roads were identified, particularly in the vicinity of bridges and tunnels, as well as the high-risk zones which overlap with ecologically significant areas, including Natura 2000 and Emerald Network sites. These findings confirm that the issue has a dual dimension of both safety-related and ecological issues which require integrated approaches in the planning and implementation of preventive measures.

The general recommendations emphasize the importance of combining strategic and infrastructural actions, while also pointing out that each identified high-risk location requires a localized approach tailored to its specific spatial and ecological characteristics. Road sections passing through karst fields and river valleys are particularly important because conflicts between transportation infrastructure and wildlife migration corridors are most pronounced in those areas.

The limitations of this research primarily stem from the lack of detailed data on the animal species involved in accidents, as well as limited information on wildlife migration routes. A more advanced statistical assessment of collision determinants, such as testing the significance of correlations between WVCs and variables like traffic intensity, vehicle speed, land cover types, or proximity to ecological habitats, could substantially strengthen future research. Incorporating regression-based or machine-learning models would enable a more precise quantification of risk factors and improve predictive capability beyond descriptive spatial patterns. Such approaches would expand the analytical depth of this study and support the development of more evidence-based mitigation strategies.

The observed clustering of collisions near bridge and tunnel locations indicates that infrastructure–habitat interfaces need closer examination. Although several collision clusters appear near bridge locations, this study did not statistically test the significance of these patterns. Further analyses are needed to verify whether such infrastructural and ecological interfaces consistently contribute to higher collision frequencies. Also, future research should investigate the role of this infrastructure using larger datasets and species-specific movement data. Such analyses would help clarify whether particular structures elevate the collision risk or offer opportunities for targeted mitigation design.

The study applied Euclidean distance to identify collision clusters, since irregular road geometry in the study area makes chainage-based distances unreliable for hotspot detection. However, future research could combine spatial clustering with chainage-based moving-window analysis to provide finer-scale identification of risk segments.

Furthermore, the study identified high-risk locations based on the number of accidents and their spatial distribution. The results indicate that the greatest risks are not exclusively linked to roads with high traffic volumes or those located near natural habitats, but also to specific segments of the road network, such as bridges and tunnels, where infrastructural features intersect with natural wildlife migration corridors. Therefore, it is necessary to conduct more detailed analyses of additional factors influencing WVCs, such as vehicle speeds on certain road sections, traffic intensity, and others. Accordingly, future research should focus on:

- applying advanced analytical methods for more accurate risk assessment that take into account a broader range of factors (e.g., vehicle speed, species vulnerability, migration corridors, etc.);
- conducting comparative analyses in regional, European, and global contexts to identify best practices;
- developing pilot projects for the implementation of wildlife overpasses, fencing, and intelligent signalling systems at priority locations;
- improving data collection systems, with explicit identification of causes and mandatory recording of the animal species involved in each wildlife–vehicle collision.

In summary, the study confirms that addressing the issue of wildlife–vehicle collisions requires integrated and spatially targeted measures that simultaneously enhance road safety and contribute to biodiversity conservation. Future efforts should focus on combining scientific analyses, strategic planning, and practical infrastructural solutions, drawing on international standards and experiences from the region and Europe.

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DATA AVAILABILITY STATEMENT

Supplementary materials and data used in this research are accessible upon request. For access, please contact the corresponding author via *alem.colakovic@fsk.unsa.ba*

REFERENCES

- Balčiauskas, L., A. Kučas, L. Balčiauskienė, 2025: A review of wildlife–vehicle collisions: A multidisciplinary path to sustainable transportation and wildlife protection. Sustainability 17: 4644. https://doi.org/10.3390/su17104644
- Bhandari, K., S. Upadhaya, N.K. Yadav, P. Poudel, B.P. Heyojoo, Y.P. Timilsina, P. Koirala, 2024: What factors drive wildlife-vehicle collisions on highways? A case study from Western Nepal. Journal of Nature Conservation 81: 126678. https://doi.org/10.1016/j.jnc.2024.126678
- Bíl, M., R. Andrášik, M. Duľa, J. Sedoník, 2019: On reliable identification of factors influencing wildlife-vehicle collisions along roads. Journal of Environmental Management 237: 297–304. https://doi.org/10.1016/j.jenvman.2019.02.076
- Dawson, C., A.M. Villamagna, R.A. Martin, R.J. Moll, 2025: More connected, more collisions? Documenting nonlinear relationships between habitat connectivity and wildlife–vehicle collision hotspots. Environmental Management 75: 2089–2102. https://doi.org/10.1007/s00267-025-02188-0
- Federalno ministarstvo okoliša i turizma, 2021: Crvena lista faune Federacije Bosne i Hercegovine. Federalno ministarstvo okoliša i turizma, Sarajevo. https://fmoit.gov.ba/wp-content/uploads/dokumenti/Crvena-lista-Faune-FBiH.pdf
- Federalno ministarstvo okoliša i turizma, 2024a: Popis Natura 2000 lokaliteta Federacije BiH. Federalno ministarstvo okoliša i turizma, Sarajevo. https://fmoit.gov.ba/okolis/zastita-prirode/popis-natura-2000-federacije-bih/
- Federalno ministarstvo okoliša i turizma, 2024b: Emerald mreža Bosne i Hercegovine. Federalno ministarstvo okoliša i turizma, Sarajevo. https://fmoit.gov.ba/okolis/zastita-prirode/emerald-mreza-bosna-i-herceovina/
- Fedorca, A., M. Fedorca, O. Ionescu, R. Jurj, G. Ionescu, M. Popa, 2021: Sustainable landscape planning to mitigate wildlife–vehicle collisions. Land 10: 737. https://doi.org/10.3390/land10070737
- Galinskaitė, L., A. Ulevičius, V. Valskys, A. Samas, P.E. Busher, G. Ignatavičius, 2022: The influence of landscape structure on wildlife–vehicle collisions: Geostatistical analysis on hot spot and habitat proximity relations. ISPRS International Journal of Geo-Information 11: 63. https://doi.org/10.3390/ijgi11010063
- Gilhooly, P.S., S.E. Nielsen, J. Whittington, C.C. St. Clair, 2019: Wildlife mortality on roads and railways following highway mitigation. Ecosphere 10: e02597. https://doi.org/10.1002/ecs2.2597
- Ha, H., F. Shilling, 2018: Modelling potential wildlife–vehicle collisions (WVC) locations using environmental factors and human population density: A case study from three state highways in Central California. Ecological Informatics 43: 212–221. https://doi.org/10.1016/j.ecoinf.2017.10.005
- Helldin, J.O., 2019: Predicted impacts of transport infrastructure and traffic on bird conservation in Swedish Special Protection Areas. Nature Conservation 36: 1–16. https://doi.org/10.3897/natureconservation.36.31826
- International Union for Conservation of Nature (IUCN), 2024: The IUCN Red List of Threatened Species. https://www.iucnredlist.org
- JP Autoceste Federacije BiH, 2024: Mapa autoputeva u Federaciji BiH. JP Autoceste Federacije BiH, Sarajevo. https://www.jpautoceste.ba/interaktivna-mapa/

- JP Ceste Federacije BiH, 2024a: Brojanje saobraćaja – PGDS podaci. JP Ceste Federacije BiH, Sarajevo. https://jpdcfbh.ba/bs/aktivnosti/brojanje-saobracaja/22
- JP Ceste Federacije BiH, 2024b: Mreža magistralnih cesta Federacije BiH. JP Ceste Federacije BiH, Sarajevo. https://jpdcfbh.ba/bs/aktivnosti/mreza-magistralnih-cesta/37
- Koju, N.P., A.K.C. Anish, K. Dodhari, P. Giri, M. Lee, S. Pokhrel, A. Ghimire, L. Nyaichyai, K.O. Onditi, X. Jiang, R.C. Kyes, 2025a: Spatiotemporal patterns and environmental determinants of wildlife–vehicle collisions in Banke National Park, Nepal. Scientific Reports 15: 19478. https://doi.org/10.1038/s41598-025-04609-w
- Koju, N.P., A.K.C. Anish, K. Dodhari, P. Giri, M. Lee, S. Pokhrel, A. Ghimire, L. Nyaichyai, K.O. Onditi, X. Jiang, R.C. Kyes, 2025b: Spatiotemporal patterns and environmental determinants of wildlife–vehicle collisions in Banke National Park, Nepal. Scientific Reports 15: 19478. https://doi.org/10.1038/s41598-025-04609-w
- Kouris, A.D., A. Christopoulos, K. Vlachopoulos, A. Christopoulou, P.G. Dimitrakopoulos, Y.G. Zevgolis, 2024: Spatiotemporal patterns of reptile and amphibian road fatalities in a Natura 2000 area: A 12-year monitoring of the Lake Karla Mediterranean Wetland. Animals 14: 708. https://doi.org/10.3390/ani14050708
- Kučas, A., L. Balčiauskas, C. Lavalle, 2023: Identification of urban and wildlife terrestrial corridor intersections for planning of wildlife–vehicle collision mitigation measures. Land 12: 758. https://doi.org/10.3390/land12040758
- Laliberté, J., M.-H. St-Laurent, 2020: In the wrong place at the wrong time: Moose and deer movement patterns influence wildlife–vehicle collision risk. Accident Analysis & Prevention 135: 105365. https://doi.org/10.1016/j.aap.2019.105365
- Laube, P., N. Ratnaweera, A. Wróbel, I. Kaelin, A. Stephani, M. Reifler-Baechtiger, R.F. Graf, S. Suter, 2023: Analysing and predicting wildlife–vehicle collision hotspots for the Swiss road network. Landscape Ecology 38: 1765–1783. https://doi.org/10.1007/s10980-023-01655-5
- Lind Hansen, J., P. Sunde, T.J. Skovbjerg Balsby, M. Mayer, 2024: Using animal–vehicle collision data for wildlife population monitoring. Ecosphere 15: e4953. https://doi.org/10.1002/ecs2.4953
- Litvaitis, J.A., J.P. Tash, 2008: An approach toward understanding wildlife–vehicle collisions. Environmental Management 42: 688–697. https://doi.org/10.1007/s00267-008-9108-4
- Malo, J.E., F. Suárez, A. Díez, 2004: Can we mitigate animal–vehicle accidents using predictive models? Journal of Applied Ecology 41: 701–710. https://doi.org/10.1111/j.0021-8901.2004.00929.x
- Medrano-Vizcaíno, P., C. Grilo, D. Brito-Zapata, M. González-Suárez, 2023: Landscape and road features linked to wildlife mortality in the Amazon. Biodiversity and Conservation 32: 4337–4352. https://doi.org/10.1007/s10531-023-02699-4
- Ministarstva unutrašnjih poslova kantona u Federaciji BiH, 2024: Evidencije saobraćajnih nezgoda 2021–2023. Ministarstva unutrašnjih poslova FBiH, Sarajevo.
- Morelle, K., F. Lehaire, P. Lejeune, 2013: Spatio-temporal patterns of wildlife–vehicle collisions in a region with a high-density road network. Nature Conservation 5: 53–73. https://doi.org/10.3897/natureconservation.5.4634
- Neumann, W., G. Ericsson, H. Dettki, N. Bunnefeld, N.S. Keuler, D.P. Helmers, V.C. Radeloff, 2012: Difference in spatiotemporal patterns of wildlife road-crossings and wildlife–vehicle collisions. Biological Conservation 145: 70–78. https://doi.org/10.1016/j.biocon.2011.10.011
- Paemelaere, E.A.D., A. Mejía, S. Quintero, M. Hallett, F. Li, A. Wilson, H. Barnabas, A. Albert, R. Li, L. Baird, G. Pereira, J. Melville, 2023: The road towards wildlife friendlier infrastructure: Mitigation planning through landscape-level priority settings and species connectivity frameworks. Environmental Impact Assessment Review 99: 107010. https://doi.org/10.1016/j.eiar.2022.107010
- Pagany, R., 2020: Wildlife–vehicle collisions – Influencing factors, data collection and research methods. Biological Conservation 251: 108758. https://doi.org/10.1016/j.biocon.2020.108758
- Park, H., M. Kim, S. Lee, 2021: Spatial characteristics of wildlife–vehicle collisions of water deer in Korea expressway. Sustainability 13: 13523. https://doi.org/10.3390/su132413523
- Quintana, I., E.F. Cifuentes, J.A. Dunnink, M. Ariza, D. Martínez-Medina, F.M. Fantacini, B.R. Shrestha, F.-J. Richard, 2022: Severe conservation risks of roads on apex predators. Scientific Reports 12: 2902. https://doi.org/10.1038/s41598-022-05294-9
- Sáenz-de-Santa-María, A., J.L. Tellería, 2015: Wildlife–vehicle collisions in Spain. European Journal of Wildlife Research 61: 399–406. https://doi.org/10.1007/s10344-015-0907-7
- Sevigny, J., A. Summers, G. Kalisz, K. McAllister, 2021: Identification of elk–vehicle incident hotspots on State Route 20 in Washington State. Landscape Ecology 36: 1685–1698. https://doi.org/10.1007/s10980-021-01238-2
- Su, H., Y. Wang, Y. Yang, S. Tao, Y. Kong, 2023: An analytical framework of the factors affecting wildlife–vehicle collisions and barriers to movement. Sustainability 15: 11181. https://doi.org/10.3390/su151411181
- Visintin, C., R. van der Ree, M.A. McCarthy, 2016: A simple framework for a complex problem? Predicting wildlife–vehicle collisions. Ecology and Evolution 6: 6409–6421. https://doi.org/10.1002/ece3.2306
- Vrkljan, J., D. Hozjan, D. Barić, D. Ugarković, K. Krapinec, 2020: Temporal patterns of vehicle collisions with roe deer and wild boar in the Dinaric area. Croatian Journal of Forest Engineering 41: 347–358. https://doi.org/10.5552/crojfe.2020.789