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Wildlife mortality on the Slovenian highways: monthly patterns, identification of hotspots and effectiveness of acoustic deterrents

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Abstract

We studied species composition and monthly patterns of roadkill of large and medium sized mammal species along 778 km of Slovenian highways in the period 2018–2020. Apart from providing the first comprehensive data on monthly patterns of roadkill as a proxy of wildlife-vehicle collisions at Slovenian highways and identifying linear collision hotspots (using KDE + methodology), we also tested the impact of acoustic deterrents installed at highway interchanges in late 2018 on WVC frequency. In the three-year period, we registered in total 2046 roadkill cases, with red fox (*Vulpes vulpes*), ($N = 790$; 39.6%), roe deer (*Capreolus capreolus*) ($N = 592$; 28.9%), and European badger *(Meles meles*), ($N = 423$; 20.7%) being the most exposed species. Temporal collision patterns with evident species-specific monthly peaks reflect the behaviour and activity of these three species. We identified 268 KDE + hotspots, accounting for 48.5% of all roadkill and covering 9.3% (72.6 km) of the highway network. Recognising these hotspots is crucial for implementing mitigation measures to reduce WVC on Slovenian highways. However, our findings indicate no decrease in roadkill after installation of acoustic deterrents (2019–2020), therefore additional effort is needed to find adequate and effective approach for reducing roadkill and hence increasing road safety.

Keywords Highway · Roadkill · Wildlife-vehicle collisions · Acoustic deterrents · Interchanges · Spatiotemporal analyses

Introduction

The recent expansion of road networks and rising traffic volumes in Slovenia and globally have had multifaceted impacts on wildlife, including: (i) creating physical and behavioural barriers; (ii) disturbances from traffic noise, vibrations, chemical pollution, and human presence; (iii) habitat loss and fragmentation; and (iv) increased mortality due to collisions with vehicles (i.e., roadkill) (Trombulak and Frissell 2000; Bekker and Iuell 2003). Wildlife-vehicle collisions (hereafter WVC) not only pose a risk to the road safety and incur significant economic losses but are also one of the main causes of wildlife mortality (Seiler 2004; Langbein et al. 2011; Lagos et al. 2012; Markolt et al. 2012; Cserkesz and Farkas 2014; Gilhooly et al. 2019; Kučas and Balčiauskas 2021).

Recent studies have shown that WVC locations are not random, but are rather clustered spatially and temporally for various vertebrate species (Gunson et al. 2011; Markolt et al. 2012; Cserkez et al. 2013; Andrášik and Bíl 2015; Červinka et al. 2015; Favilli et al. 2018; Jakubas et al. 2018; Bíl et al. 2019). The identification of temporal and spatial WVC patterns, including the identification of hotspots — i.e., areas where collisions occur more frequently than expected (Anderson 2009; Favilli et al. 2018; Bíl et al. 2019) — is crucial for effectively mitigating WVCs (Ramp et al. 2005; Anderson 2009; Langbein et al. 2011; Gunson et al. 2011; Cserkez et al. 2013; Favilli et al. 2018; Bíl et al. 2019; Nezval and Bíl 2020; Laube et al. 2023). Moreover, hotspots, typically covering a small portion of the total transport network length, are ideal for targeted mitigation measures (Bíl et al. 2016, 2019, 2020).

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In Slovenia, over 115,800 cases of wild ungulate roadkill were registered in the Central Slovenian Hunting Information System (hereafter Oslis) between 2002 and 2020. In recent years, more attention has been dedicated also to WVC on highways, although roadkill on Slovenian highways (which are completely fenced with solid mesh fences along both sides) represents < 7% of all registered traffic mortality, i.e. both on roads and railways (Al Sayegh Petkovšek et al. 2023). In terms of road safety, particularly problematic is the access of large mammals on the highway due to several reasons: the speed of vehicles there are much higher; safe removing or harvesting of animals inside the fence is not possible without total block of traffic; this would cause major traffic congestion. Therefore, solving the WVC issue on fenced highways differs from approaches that can be implemented at other, less frequent roads. Nevertheless, very few studies addressed WVC on highways globally: in the systematic review of 191 WVC studies, only 26 included highways, and only 6 of them were from Europe (Pagany 2020).

In the case of a high-quality design of the protective fence, the highest probability for large mammals to enter the highway is at the interchanges, where the protective fence cannot be placed (Cserkez et al. 2013; Sedonik et al. 2023). Therefore, highway interchanges represent a kind of ecological trap for animals, as they allow them to enter the highway relatively easily, while exiting is significantly more difficult. In this case, it makes sense to completely prevent the entry of wild animals at the interchanges. With the aim to reduce the number of wild animals crossing onto the highways, acoustic deterrents were installed in the end of 2018 at interchanges on the entire Slovenian highway network.

Our study aims to provide the first comprehensive insight into traffic-related wildlife mortality on Slovenian highways and its temporal patterns. The objectives were as follows: (i) to investigate species composition of roadkill of large and medium size mammals; (ii) to better understand temporal patterns of WVC on highways since there is still research gap regarding this issue; (iii) to investigate whether the mating period affects the monthly patterns of roadkill of individual species; (iv) to determine hotspots of WVC along fenced highways; (v) to compare roadkill before (2018) and after (2019, 2020) installation of acoustic deterrents at highway interchanges.

Materials and methods

Study area (highway network) and installation of acoustic deterrents

The study was conducted along Slovenian highway network, traversing also regions with high densities of wild ungulates and carnivores as over half of Slovenia's land is forested (Stergar et al. 2009; Skrbinšek et al. 2019). Distribution areas of ungulates, which have the highest relative density, covers 79.2%, 46.0%, 35.8%, and 21.9% of territory of Slovenia for roe deer, wild boar, red deer, and chamois (Stergar et al. 2009).

The Slovenian highway network comprises five highways and five expressways excluding interchanges, the combined length of highways and expressways is 616 km, which extends to 779 km when including interchanges. Highways are fenced along the entire length and are not electrified. Wildlife fences consist of wire mesh fixed with poles. Height of fences varied between 1,8 m and 2,2 mm (in general around 2,0 m). The speed limit on Slovenian highways is 130 km/h. In general, in each direction there are two traffic lanes (width of each: 3.7 m), emergency lane (2.5 m), and road shoulder (0.5 m). The traffic volume varies significantly along the network, with the Ljubljana Ring Road averaging 87,000 vehicles per day and individual interchanges only 223 vehicles per day (DARS 2022). The highway network is managed and maintained by the Motorway Company of the Republic of Slovenia (hereafter DARS).

In the second part of December 2018, acoustic deterrents were installed at points where the protective fence terminates, particularly at highway interchanges, to prevent wildlife access to the highways. Acoustic deterrents (EUROCONTOR Ecopillars) provide a series of signals at differing frequencies ranging from infrasound through to ultrasound; the sound is emitted at regular intervals. They were integrated into the roadside pillars at 98 interchanges, totalling 667 units. Eight deterrents were typically installed at each interchange (see Fig. 1 as an example). In accordance with past practice in Slovenia (Pokorny et al. 2008, 2016) and the possibility of using horizontal road signalling (roadside pillars), a sound is emitted at height around 0.5 m, which also corresponds to the height of most of the studied wildlife species and especially the species with the largest roadkill (red fox, European roe deer).

Installation of acoustic deterrents was chosen due on past experiences in solving the problem of wildlife roadkill on the Slovenian roads. Acoustic deterrents were tested in Slovenia (Pokorny et al. 2008; 2016; Al Sayegh Petkovšek et al. 2020), Germany (Voss 2007), England (Langbein 2007; Langbein et al. 2011), and Austria (Schalk et al. 2023). In

Fig. 1 One of the highway interchanges, showing general principle of installation of acoustic deterrents (red dots)

Slovenia the installation of acoustic deterrents along problematic road sections, significantly reduced the number of road-killed roe deer, especially shortly after the installation of deterrents. However, the efficiency of acoustic deterrents elsewhere still remains unproven and may depend on signal type and variability (problem of rapid habituation by animals), and especially maintaining, weather conditions and geographic position, which directly impact activity of providing signals (Pokorny et al. 2016; Putman and Langbein 2024).

Data analysis

In this study, we utilized roadkill data provided by DARS, which includes information on road-killed species, date of collision, and location (with accuracy < 100 m). Highway staff conducted daily road inspections, recording each accident, removing carcasses, and forwarding them to Veterinary services.

Our analysis spanned from 2018 to 2020. We did not target all animal species from the database but rather focused on large and medium-sized mammals for which data are expected to be more comprehensive and precise in comparison with birds and small mammals; we also excluded domestic animals. Moreover, targeted species are large enough to represent threat to traffic safety, and are as follows: roe dee, red deer (*Cervus elaphus*), wild boar (*Sus scrofa*), brown bear (*Ursus arctos*), golden jackal (*Canis aureus*), red fox, European badger, and brown hare (*Lepus europaeus*). For the monthly distribution of roadkill, we focused on four species with the highest registered roadkill: roe deer, red fox, European badger, and brown hare. We employed the Kruskal-Wallis test with Dunn's post-hoc test to discern differences in monthly roadkill frequencies.

To test an assumption that implementation of acoustic deterrents at highway interchanges decreases wildlife mortality we compared the collision rates, i.e. the number of collisions per km per year (Carvalho et al. 2017; Gilhooly et al. 2019), for studied species before (year 2018) and after (2019–2020) the implementation of deterrents. Additionally, the frequency (proportion) of roadkill registered on interchanges *versus* other parts of highways was compared for each year. The comparison was made for the entire highway network and proportion test was used for this purpose as it compares the proportion of a certain attribute or characteristic across different groups or time periods. Considering previous findings that interchanges influence WVC rate up to 400 m away (Cserkesz et al. 2013) as well as spatial and technical characteristics of Slovenian highway interchanges, we decided for defining 500 m influential section of each interchange along both sides of the highway as the "interchange section".

For hotspots identification along the highway, we used the KDE + software (Bíl et al. 2016; Nezval and Bíl 2020 and Bíl et al. 2020). This approach extends the standard kernel density estimation (KDE) by repeated random simulations (Monte Carlo method). According to Nezval and Bíl (2020), the advantage of this method is that only statistically significant clusters (hotspots) are determined. To further prioritize among the identified hotspots, the highest collective risk level was utilized. This parameter is particularly valuable in wildlife-vehicle collision (WVC) studies, where the aim is to identify road segments that contribute the most to overall collision rates. In this context, the KDE + software automatically ranks hotspots based on incident density and clustering significance, allowing users to quickly pinpoint the highest-risk areas for targeted interventions (Bíl et al. 2016).

Results and discussion

Mammal roadkill according to species involved

Over the three-year period (2018–2020), a total of 3,348 collisions resulting in roadkill of animals were registered on the Slovenian highways (778 km), with 2,046 involving eight target mammalian species as follows: 790 red foxes, 592 European roe deer, 423 European badgers, 186 brown

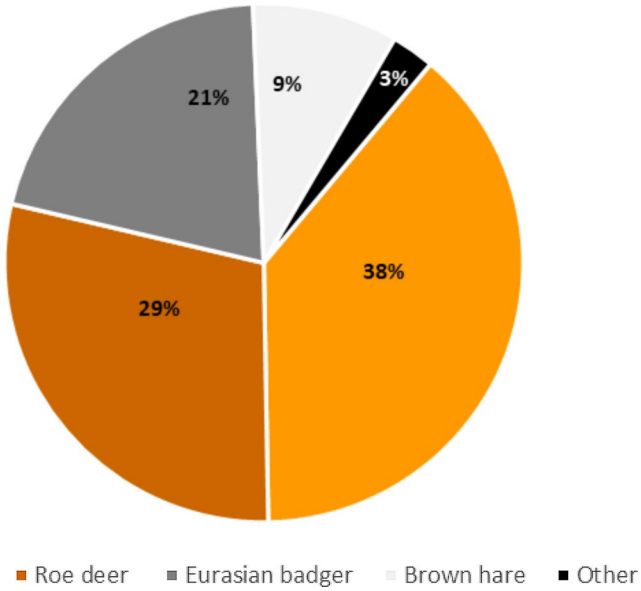

Fig. 2 Frequency of roadkill per species across all three years; in the group "other" we've included wild boar, golden jackals, red deer and brown bears

Table 1 Review of roadkill rates (no. of individuals/km/year) for selected wildlife species in different countries(sources: Markolt at al. 2012[a]; Cserkesz et al. 2013[b]; Cserkesz and Farkas 2014[c]; Jakubas et al. 2018[d])

	Slovenia: entire highway network (778 km), 2018–2020 (this study)	Hungary: entire highway network (1314 km), 2000–2010[b, c]	Hungary: M3 highway (223 km), 2002–2009[a]	Poland: expressway (38 km), 2010–2013[d]
Red fox	0.34	0.35	0.70	0.31
European roe deer	0.25	0.04	0.05	0.24
European badger	0.18	-	0.06	0.14
Brown hare	0.08	-	-	-
Wild boar	0.01	0.13	0.03	0.36
Red deer	0.005	-	-	0.01

hares, 27 wild boar, 13 golden jackals, 12 red deer, and 3 brown bears, respectively (Fig. 2).

The highest roadkill at Slovenian highways was registered in case of red fox (38%; 0.34 individuals per km per year), followed by roe deer (29%; 0.25), European badger (21%; 0.18), and brown hare (9%; 0.08). In general, ungulates are major taxa exposed to vehicle collision along all types of roads, due to their foraging in open areas, which increases their road-crossing frequency (Langbein and Putman 2005; Pokorny 2006; Langbein et al. 2011; Cserkesz et al. 2013; Vrkljan et al. 2020; Bíl et al. 2021; Bíl et al. 2023). However, our study showed that at highways red fox is the most vulnerable mammal species considering risk for road mortality. This finding strongly contradicts to registered roadkill on all Slovenian roads (including highways), where the number of road-killed roe deer in the same period (2018–2020) was fourfold higher in comparison with road-killed red fox (13,517 vs. 2,882) (Oslis 2023). A very large proportion of collisions with red fox was also found along MR3 highway in Hungary, where more than 80% of all registered WVCs involved red fox, and where badger, roe deer and wild boar composed 7.5%, 5.9%, and 5.3% of roadkill, respectively, regardless that population density of roe deer was estimated to be nearly fivefold higher in comparison with red fox (Markolt et al. 2012). They concluded that roadkill frequency at highways is related more to vagility and specific behaviour characteristics of red fox than its local population density, because red fox can easily find a way through the fencing at small diggings. Indeed, our own field inspection at Slovenian highways also confirmed that mesocarnivores (red fox, badger) are able to enter and try to cross the highways through damaged fence or beyond it (e.g., by digging under the fence).

Table 1 presents a comparison of roadkill rates for selected wildlife species in three European countries. Despite limited research on highway-specific collision rates, our findings suggest that the mammal roadkill at Slovenian highways is comparable to other Central European countries (Markolt et al. 2012; Cserkesz et al. 2013; Jakubas et al. 2018), with red fox having in all these countries very same frequency of road-killed individuals/km of highway.

Seasonal pattern of mammal roadkill

We analysed the monthly distribution of roadkill for four species (European roe deer, red fox, European badger,

brown hare), which accounted for 97% of recorded roadkill of large and medium-sized mammals at Slovenian highways in the studied three-year period. The remaining four species were excluded from the analysis due to the small sample sizes.

We observed a significant variation in the monthly distribution of roe deer roadkill (Kruskal-Wallis test: H = 27.935, df = 11, $p = 0.003$; $n = 592$), with pronounced peaks in April and May (Fig. 3a). This finding aligns with various studies on temporal pattern of collisions with roe deer and its roadkill along all road types (Langbein and Putman 2006; Pokorny 2006; Lagos et al. 2012; Markolt et al. 2012; Šprem et al. 2013; Steiner et al. 2014; Kusta et al. 2017; Vrkljan et al. 2020; Putman and Langbein 2024). Very evident spring peak coincides with the period when roe deer establish territories and have increased food demands (Langbein and Putman 2005; Pokorny 2006; Lagos et al. 2012; Šprem et al. 2013). In these two months, more than 50% of roe deer vehicle collisions occur in Europe (Groot Bruinderink and Hazebroek 1996). However, contrary to reports of increased collision risks in summer and autumn due to higher fawn activity and maize field clearing (Pokorny 2006; Morelle et al. 2013; Steiner et al. 2014; Bíl et al. 2023), including at other roads in Slovenia for investigated period (Fig. 3a) (Oslis 2023), this secondary peak does not appear to be present at Slovenian highways. Obviously, fences along highways effectively block roe deer wandering across highways in summer and autumn, while they are not so effective during much more intensive spring movements due to social restructuring, i.e. establishing territories, or dispersion of yearlings. However, we could not exclude, that this might be the consequence of damages of fence during the winter and before mating period in spring.

The yearly roadkill of red fox shows bimodal pattern (Kruskal-Wallis: H = 19.505, df = 11, $p = 0.052$; $n = 790$; Fig. 3b). The two peaks occur in January and during late summer to autumn (September–November). The autumnal peak aligns with findings from the M3 highway in Hungary, where a higher frequency of collisions with red fox was observed in September and October (Markolt et al. 2012).

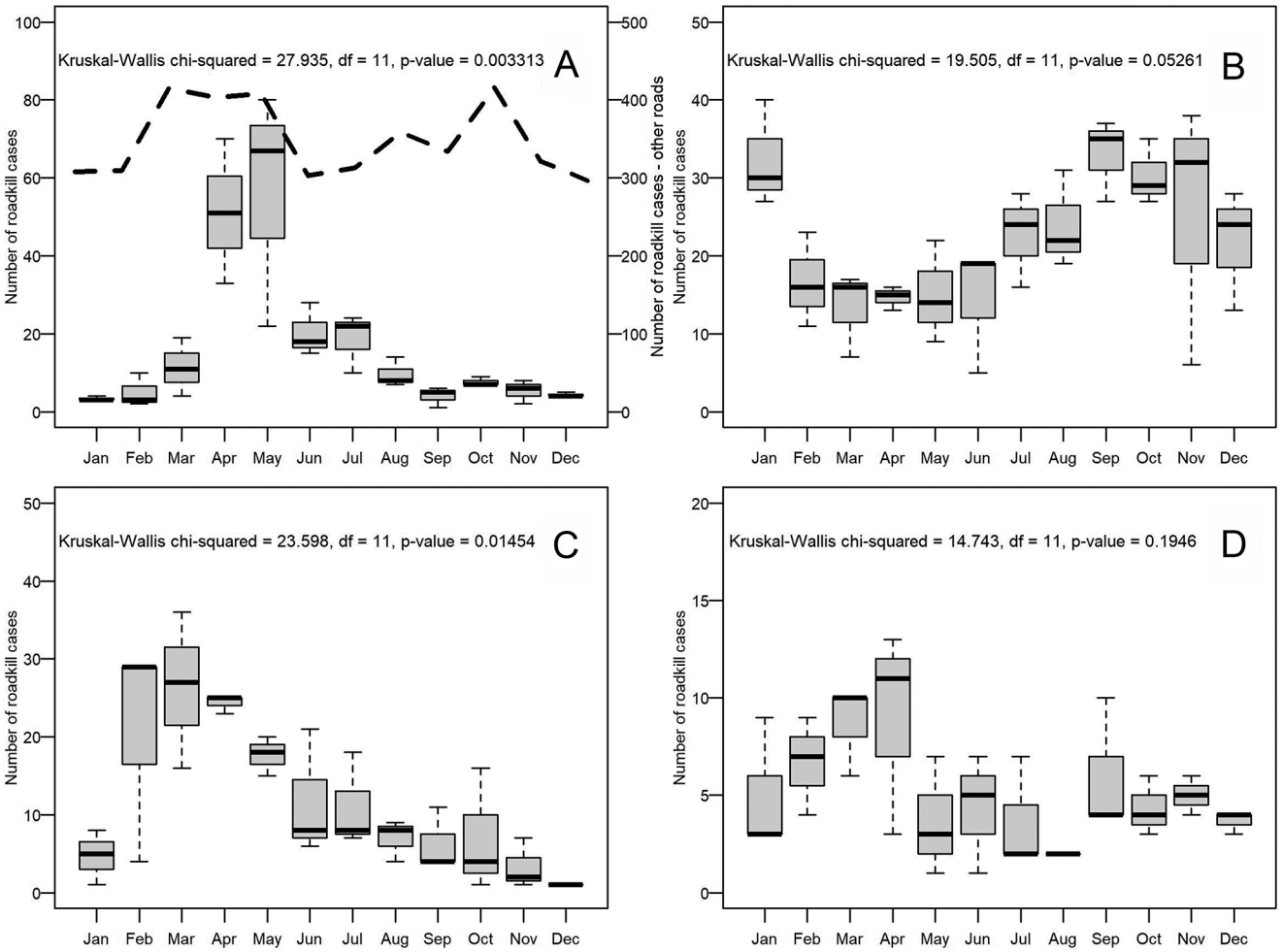

Fig. 3 Monthly roadkill of four mammal species at Slovenian highways in the period 2018–2020: **A** – European roe deer; **B** – red fox; **C** – European badger; **D** – brown hare. Monthly roadkill of European roe deer at other roads is marked with the dashed line

Similar patterns were noted in southern Belgium (Wallonia) between 2003 and 2011, with peaks in January, May, and October–November (Morelle et al. 2013). The increased road mortality of red fox in September and October is likely due to the dispersal of subadults seeking new territories (Rushton et al. 2006; Morelle et al. 2013). On the contrary, a very evident January peak may be attributed to the mating activity of foxes, which typically occur from January to early February in Slovenia (Kryštufek 1991; Leskovic 2012).

Yearly seasonal pattern of the roadkill of badgers at Slovenian highways is also very clear (Fig. 3c): collisions with this species dramatically increased in the February and March, and the peak period ceased with May (Kruskal-Wallis: $H = 23.598$, $df = 11$, $p = 0.0145$; $n = 423$). This finding echoes observations from eastern Poland, where 80% of female badgers were road-killed during the spring-summer months (March–June), a period when nursing females expand their territories in search of food (Kowalczyk et al. 2006; Nowakowski et al. 2022). However, an increase in roadkill was previously also noted during October, for example in Denmark (Dekker and Bekker 2010). The species has multiple mating periods during the year, due to which we had registered in Slovenia a complex pattern in the reduction of road mortality due to covid-19 related lockdowns in 2020, with partially compensatory dynamics, i.e. with a significant increase of autumnal roadkill of badgers after very high reduction of road mortality in spring (March–April), when in normal years the road mortality of the species is the highest (Pokorny et al. 2022). As polyoestrous species, badgers can mate at any time of the year, but the main mating peak occurs in spring (between February and May), and can be followed by a second one in autumn, involving either females that had not been previously fertilized or the ones which experienced superfetation (Yamaguchi et al. 2006; Harris and Yalden 2008; Corner et al. 2015). Consequently, this species often showed two, i.e. spring and autumnal peaks in yearly traffic collision dynamic as was observed in the south of England (Davies et al. 1987). Nevertheless, such bimodal pattern of roadkill of European badger at Slovenian highways was not detected, showing that either adults reproducing in summer/autumn, or the second yearly cohort of offspring have different movement behaviour, i.e. they have lower need to cross highways in comparison with the spring time.

Among the four species analysed, roadkill of brown hare was the least frequent and with a more uniform temporal distribution across months (Kruskal-Wallis: $H = 14.743$, $df = 11$, $p = 0.1946$; $n = 186$; Fig. 3d). However, it is important to consider that the actual number of collisions with brown hares as well as its roadkill might be much higher than recorded, due to their small body size and lower visibility, leading to undetected mortality cases. Studies conducted in various landscapes have shown that hares tend to cross roads more frequently during the spring mating season compared to the rest of the year (Mayer et al. 2023). In line with this, we also observed a spring peak in roadkill (February–April), which was, however, significantly higher only in comparison with August.

Identification of hotspots of WVC

To identify hotspots of WVC along Slovenian highway sections, we employed the KDE + clustering method (Bíl et al. 2013, 2016; Andrašik and Bíl 2015; Favilli et al. 2018). During the study period, a total of 268 KDE + hotspots were identified, containing 992 roadkill locations (48.5%) with eight mammal species. These hotspots cover 72.6 km and represent 9.3% of the entire Slovenian highway network. The number of road mortality cases at these hotspots ranged from 2 to 14, with hotspot lengths varying from 100 m to 900 m. Over half of the identified hotspots (61.2%) contained three or fewer roadkill cases. To pinpoint the most critical hotspots, we selected those with the highest collective risk level ($CR > 1$) and a minimum of 6 reported roadkill cases (2 per year), as shown in Figs. 4 and 5 and Table S1.

Prioritizing the most significant hotspots for targeted mitigation measures is a strategy supported by numerous studies (Ramp et al. 2005; Bíl et al. 2013, Bíl et al. 2019; Shilling and Waetjen 2015; Favilli et al. 2018; Nezval and Bíl 2020; Laube et al. 2023; Sedonik et al. 2023). According to Favilli et al. (2018), ranking hotspots is crucial for optimizing site inspection time and reducing costs of mitigation measures. We believe that identified hotspot locations (Fig. 4), spanning 23 different highway sections, will enable decision-makers (DARS company) to select and implement the most effective mitigation strategies. Moreover, according to several reviews the best strategies for reduction of roadkill is the use of several complementary measures (e.g., enhancing the protection of interchanges, ensuring the functionality of existing fences and wildlife passages, proposing new bridging facilities, initiating driver awareness campaigns, and installing deterrents at rest stops) (Seiler et al. 2016; Huijser et al. 2021; Putman and Langbein 2024).

Roadkill before and after implementation of mitigation measures

Table 2 present a total number of road-killed individuals before installation of acoustic deterrents at highway interchanges in the second part of December 2018, and afterwards (2019, 2020). Despite installing acoustic deterrents,

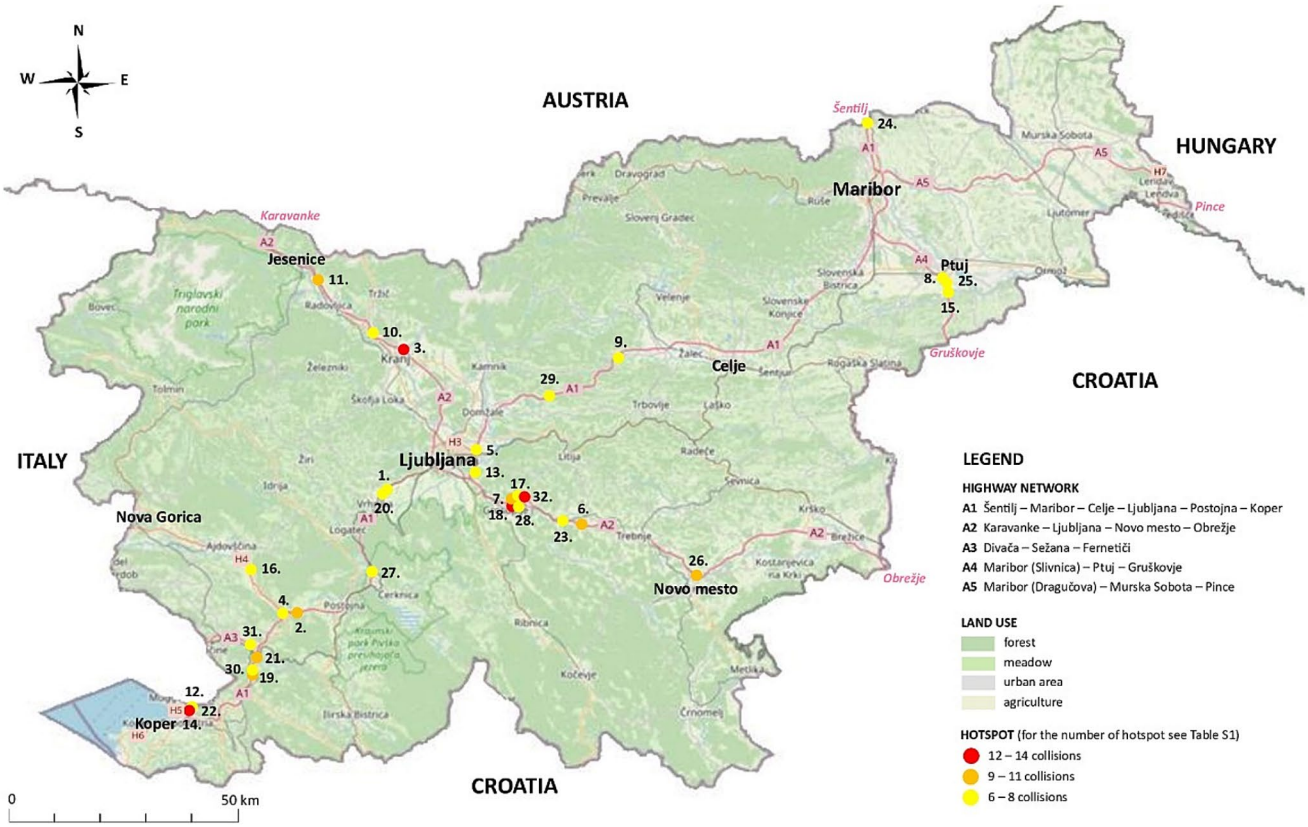

Fig. 4 The most important wildlife roadkill hotspots on the Slovenian highway network, identified between 2018 and 2020 and ranked by collective risk (CR). The hotspots parameters are listed in Table S1

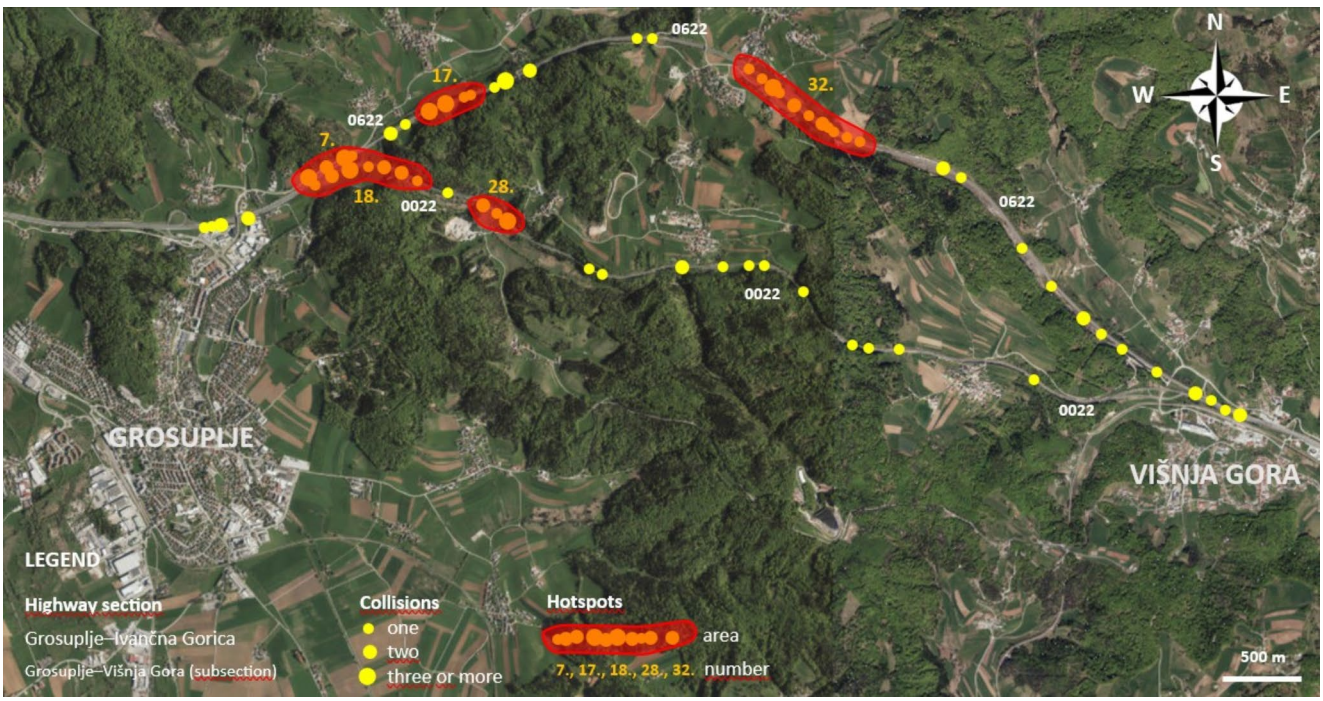

Fig. 5 Examples of the most important wildlife roadkill hotspots on the Slovenian highway network, identified between 2018 and 2020. The hotspots parameters are listed in Table S1

Table 2 Total number of road-killed individuals and collision rates recorded over the entire highway network (778 km) before (2018) and after (2019–2020) installation of acoustic deterrents at the highway interchanges

Species	2018	2019	2020	Total
Red fox	195	316	279	790
European roe deer	110	238	244	592
European badger	97	139	187	423
Brown hare	57	56	73	186
Wild boar	1	14	12	27
Golden jackal	1	2	10	13
Red deer	4	6	2	12
Brown bear	1	1	1	3
	466	**772**	**808**	**2046**
RR-8 (no. of individuals/km/year) *	**0.6**	**1.0**	**1.0**	**0.9**
RR-3 (no. of individuals/km/year) **	**0.2**	**0.3**	**0.3**	**0.3**

Note: *: RR-8: roadkill rate for all 8 studied mammal species; **: RR-3: roadkill rate for three species of wild ungulates (European roe deer, red deer, wild boar)

the total registered roadkill increased from 466 individuals in 2018 to 808 in 2020 (Table 2; Fig. 6).

The annual collision rate for all eight studied species were the lowest in 2018 (0.6 individuals/km) and the highest in 2020 (1.0 individuals/km), and for three ungulate species it increased from 0.2 individuals/km in 2018 to 0.3 individuals/km in 2019 and 2020.

The proportion of roadkill's near interchanges (≤ 500 m away on both sides of the highway) was tested by a proportion test and interestingly, it remained stable during the whole period (proportion test: 27%, 26% and 26% in 2028, 2019 and 2020; $p = 0.91$) (Fig. 6). The proportion of ungulate (roe deer, red deer, wild boar) roadkill near interchanges changed more across the three years (proportion test: 26%, 22%, 32%); however, the differences among years were not statistically significant ($p = 0.11$). Since the majority of roadkill (74%) occurred outside a 500-m radius of highway interchanges in all three years (Fig. 6), it seems that interchanges are not the main locations enabling animals to enter the highway network. This finding aligns with the study along D10 and D11 motorways in Czechia (Sedonik et al. 2023), where was shown that improper design of fencing induced WVC occurrence.

Our results indicated that the implemented mitigation measure (acoustic deterrents) did not reduce roadkill/collisions neither for the eight studied mammal species nor for ungulates alone. However, considering year-to-year variability of roadkill, also other factors should be considered, especially potential interannual changes in local population densities (natural factor) of studied species, traffic volume and start of hunting seasons (anthropogenic factors) which can significantly affect the frequency of collisions with animals (Saint-Andrieux et al. 2020; Su et al. 2023; Putman and Langbein 2024). Under normal condition (in years 2018 and 2019), the interannual variability of traffic volume on Slovenian highway was very small (only 1% considering annual average daily traffic). In year 2020 the moderate reduction of traffic volume was observed due to two COVID-19 lockdowns. However, it should be noted that although lockdown(s) in 2020 significantly reduced WVCs on roads across Europe (Bíl et al. 2021) as well as Slovenia (Pokorny et al. 2022), due to geographic position and importance of Slovenian highways for traffic connectivity from north to south and from east to west of the continent, the lockdowns did not affect importantly traffic frequency at Slovenian highways in 2020 (decrease for approx. 20%). We can summarize that traffic volume did not affect interannual variability of roadkill.

A further factor, which can contribute to roadkill, is the start of hunting season (Etter et al. 2002). The largest roadkill of roe deer, which is wildlife species with the highest culling in Slovenia, is in the spring period, when hunting seasons for females of roe deer not started yet. The last

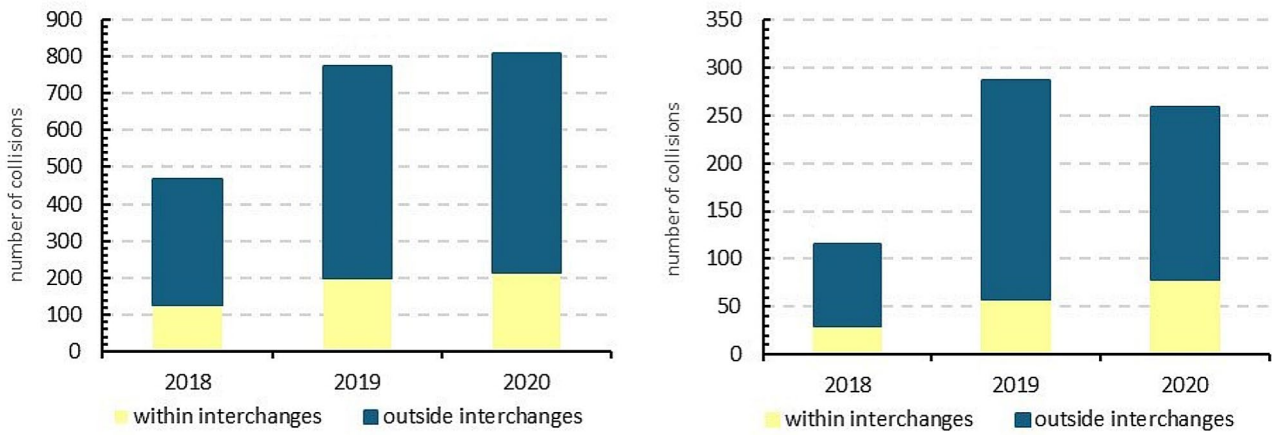

Fig. 6 Roadkill of eight mammal species (left) and three ungulate species (right) occurred within and outside the 500 m radius of highway interchanges before (2018) and after (2019 and 2020) implementation of acoustic deterrents

indicate that hunting season is probably not the important factor, which impact roadkill.

A very evident mast year, i.e. abundant beechnut, acorn, and chestnuts fruitification, in 2018 in Slovenia (Perko 2014; SFS 2019) may have contributed to increased wildlife population (especially ungulates) in subsequent years 2019 and 2020, which might also affect the roadkill in the three studied years (also after protection of interchanges). Therefore, to evaluate the impact of mitigating measures more realistically, the observation period must be extended to eliminate high interannual variability in the population density of investigated mammal species, and roadkill/collision registration by employees of highway agency should be upgraded and standardized by using system based on GPS navigators and mobile technologies.

We can summarize that on highways, despite high costs, fencing remains the most effective measure in reducing roadkill of wildlife (Putman and Langbein 2024). However, fence should be rigorously maintained and proper designed. Buried fences are particularly important in areas where wild boar, badger and red fox have high local densities (Rosell et al. 2022; Putman and Langbein 2024). Nevertheless, fences are effective and suitable mitigation measures only in combination with wildlife crossings, which compensate their negative barrier effect (Iuell et al. 2003; Langbein et al. 2011). On the other hand, problem of entering of animals through the interchanges still remain and should be properly addressed. One of possibilities are acoustic deterrents, which are the topic of the present study and study done on the Hungarian highways (Cserkesz et al. 2013). In review done by Putman and Langbein (2024) was also proposed consideration regarding the installation of wildlife grids (guards) near fence end-runs, to prevent animals enter on the highway. In the US, wildlife guards have tested with promising results, achieving efficiencies of 50–89% in ungulates (Allen et al. 2013; Flower 2016; Putman and Langbein 2024). Moreover, all measures aimed at drivers are also important (e.g., public information campaigns, dynamic warning signals).

Conclusions

On the basis of the providing results of study, which provides the first insights into roadkill of eight large and medium size mammal species along entire Slovenian highway network, the following highlights can be made:

- Our study showed that at highways red fox is the most vulnerable mammal species considering risk for road mortality (38% roadkill cases) followed by roe deer (29%) and European badger (21%). This finding strongly contradicts to registered roadkill on all Slovenian roads (including highways), where the number of road-killed roe deer in the same period (2018–2020) was fourfold higher in comparison with road-killed red fox. The high rate of red fox collisions suggests their ability to access highways through damaged fencing, aligning with findings from other Central European countries and our own field inspection at Slovenian highways. On the other hand, fences are quite effective in keeping ungulates out.
- Temporal collision patterns with evident species-specific monthly peaks reflect the behaviour and activity of investigated species (European roe deer, red fox, European badger) with some exceptions. Contrary to reports of increased collision risks in summer and autumn due to higher fawn activity and maize field clearing, this secondary peak does not appear to be present at Slovenian highways. Obviously, fences along highways effectively block roe deer wandering across highways in summer and autumn, while they are not so effective during much more intensive spring movements due to social restructuring, i.e. establishing territories, or dispersion of yearlings. Further, bimodal pattern of roadkill of European badger at Slovenian highways was not detected, showing that either adults reproducing in summer/autumn or the second yearly cohort of offspring have different movement behaviour, i.e. they have lower need to cross highways in comparison with the spring time.
- We identified 268 KDE + hotspots, accounting for 48.5% of all roadkill and covering 9.3% (72.6 km) of the highway network. Recognising these hotspots is crucial for implementing mitigation measures to reduce wildlife vehicle collisions on Slovenian highways. We believe that identified hotspot locations will enable decision-makers (DARS company) to select and implement the most effective mitigation strategies. We already tested the installation of acoustic deterrents at interchanges. However, our findings indicate no decrease in roadkill after installation of acoustic deterrents, therefore additional effort is needed to find adequate and effective approach for reducing roadkill and hence increasing road safety.

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Author contributions S.A.S.P., K.B. and K.K. wrote the first draft of the manuscript (orginal scientific paper), and B.P. was actively in-

volved in reviewing it. K.B. run KDE+ and all statistical analyses. All authors have read and agreed to the published version of the manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethical approval No approval of research ethics committees was required to accomplish the goals of this study.

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