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RESEARCH ARTICLE

Spatial Determinants of Animal Roadkill Occurrence and Hotspots, With Implications for Wildlife Conservation Along Nairobi-Mombasa Highway

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ABSTRACT

The continuous expansion of global road networks, driven by increasing human populations, poses an emerging threat to animal populations through vehicle collisions. This study identifies the causal factors and hotspots of animal roadkill along a 72 km stretch of the Nairobi–Mombasa Highway (from Kyumvi to Sultan-Hamud) and recommends appropriate mitigation measures to enhance wildlife conservation. Data on roadkill incidents were collected from 2013 to 2018 through road patrols conducted by field scouts. Environmental variables, including water points, corners, vegetation, culverts, migratory routes, settlements, slopes, land use, and fences, were gathered using Geographic Information System (GIS) techniques. A presence-absence binary logistic regression model within a GIS environment was employed to identify significant environmental drivers of roadkill and to map hotspots. A total of 408 roadkill incidents (0.944 roadkill $km^{-1} y^{-1}$) were recorded, comprising 51 species from six animal groups. Wild herbivores (13 species) and carnivores (14 species) constituted the majority of the documented wildlife, with a density of 0.204 and 0.157 fatalities per kilometre of road per year, respectively. Roadkill incidents for all species combined were significantly higher in areas near migratory routes, settlements, culverts, and corners, while they were lower in grassland, dwarf shrub grassland, open shrub areas, and near fences. However, the roadkill of different animal groups was influenced by distinct sets of factors. Most roadkill hotspots were located between Konza Center and Salama Town, with birds having the shortest stretch and herbivores and carnivores having the longest stretches. Roadkill can be mitigated by establishing road signs, fences, speed bumps, overpasses, and underpasses, and maintaining a cleared vegetation zone along the road. These findings can assist wildlife managers and infrastructure engineers in incorporating wildlife welfare and the concerns and attitudes of local communities when planning and developing linear infrastructure projects.

1 | Introduction

The movement of people and goods is crucial for economic growth, and linear infrastructure such as roads, railroads, and canals serve as essential components of modern human societies. Roads offer a cost-effective means of promoting economic development, encouraging regional trade, and providing access to natural resources and areas suitable for agricultural practices. Recently, the development of linear infrastructure has steadily increased, and global rates of construction are projected to continue rising. By 2050, global road networks are expected to reach 25 million km, with 90% of this expansion occurring in developing countries (Seto et al. 2016). Most infrastructural development is anticipated to take place in developing regions, particularly in South America, Europe, and Africa (Seto et al. 2012), which are home to pristine ecosystems and high biodiversity. These infrastructural developments will likely lead to increased road traffic, posing a significant threat to biodiversity conservation unless effective mitigation measures are implemented. Many road engineers strive to create efficient transportation systems that facilitate economic growth and development, but they rarely tackle the challenge of ensuring that these roads minimise environmental impacts and protect biodiversity. Unfortunately, policies in most developing countries do not adequately address road development issues related to wildlife or livestock movements.

Countries in Africa, including South Africa, the Democratic Republic of the Congo and Kenya, face significant challenges primarily due to the conversion of existing small roads into high-speed highways with heavy traffic volumes (Gubbi et al. 2012; Collinson et al. 2015). In recent years, the Congo Basin has seen over 50,000 km of new roads bulldozed into the rainforest by industrial loggers. Road transport is the predominant mode of transportation in Kenya, and the demand for access and mobility has led to the development of a primary road system that spans approximately 160,886 km as of 2015. Additionally, Kenya plans to construct and rehabilitate around 5500 km of roads by 2030 (Kenya Rural Roads Authority 2017).

Roads impact wildlife and other animals both directly and indirectly. The road network can fragment habitats into small patches, creating metapopulations with restricted movements and barriers to historical corridors (Vos and Chardon 1998). This fragmentation leads to the functional isolation of populations due to reduced access to essential habitats. Areas cleared for road development directly contribute to habitat degradation while facilitating the invasion of weeds and pest animals, inducing noise-related psychological and behavioural changes, altering microclimates, and increasing human-led resource exploitation. These factors result in elevated rates of encroachment, poaching, and wildfires (Forman et al. 2003). Road planners require straightforward models to identify road sections where the risk of animal-vehicle collisions is predictably high and where permanent mitigation measures would be effective in the long term (Malo et al. 2004). Another direct negative impact of roads is the occurrence of roadkill among diverse wildlife and other animals. Roadkill occurs when vehicles collide with animals, with collision distribution being generally heterogeneous (Gunson et al. 2011; Kambourova-Ivanova et al. 2012; Kioko et al. 2015; Kiffner et al. 2015). Road collisions are more likely to occur on paved sections of the road with higher traffic speeds, as well as in areas surrounded by dense vegetation, which impairs driver visibility (Lala et al. 2021; Van Niekerk and Eloff 2005; Farmer and Brooks 2012). In urban-wildlife interface areas, the presence and migration of animals, particularly ungulates, significantly increase the risk of collisions, as these animals are now closer to roadways (Kreling et al. 2019). For clarity, significant predictors are categorised as either positively or negatively influencing wildlife-vehicle collisions (WVCs), following the approach of Gunson et al. (2011).

This study was conducted along the Nairobi-Mombasa highway (NMH), which is the oldest and busiest road in Kenya, which connects the coastal region to the landlocked countries of East and Central Africa. Due to the recent increase in the number of vehicles using the highway, the Kenyan government is expanding the existing single-carriageway into a dual-carriageway to accommodate the growing traffic volumes (Kenya Rural Roads Authority 2017). However, these expansions, along with other factors, may have detrimental effects on wildlife that need to be addressed. Therefore, this study aims to identify the causal factors and hotspots of wildlife roadkill along the NMH and propose effective mitigation measures.

2 | Methods

2.1 | Study Area

The NMH, also known as Road A109, is the primary route connecting the cities of Mombasa and Nairobi, spanning 482 km. The major cities and towns along this highway are Nairobi, Athi River, Salama, Sultan Hamud, Emali, Kibwezi, Voi, Samburu and Mombasa. The study area consisted of a 500 m buffer zone along a 72-km long stretch between Sultan Hamud (latitude: 2°1′71′7.04″ S and longitude: 37°22′722′7.42″ E) and Kyumvi (latitude: towns (Latitude: 1°31′5831′58.11″ S and longitude: 37°7′557′55.19″ E)) (Figure 1). The road traverses areas characterised by human settlements, as well as crop and livestock farming, with vehicle speed limits ranging from 50 to 100 km/h.

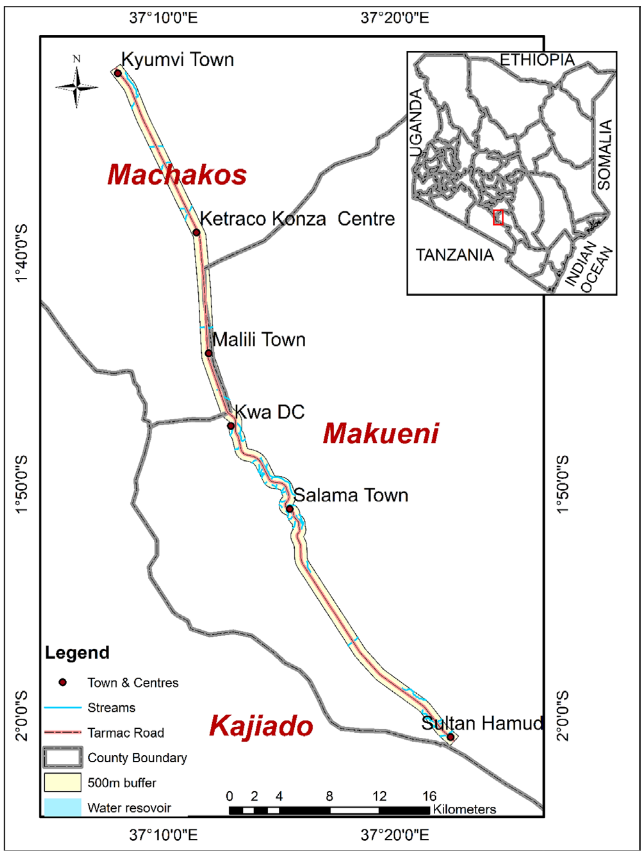

FIGURE 1 | Study area map showing the 500 m buffer along the 72 km stretch of highway between Kyumvi and Sultan Hamud towns.

2.2 | Data Collection

2.2.1 | Wildlife and Non-Wildlife Animal Fatality Surveys

Counts of wildlife and non-wildlife animal fatality surveys along the 72-km stretch of highway between Kyumvi and Sultan Hamud towns were opportunistically recorded from 2013 to 2018 by staff from Action for Cheetahs in Kenya (ACK), providing long-term secondary data. In the final 3 months of the study, two field scouts, a researcher, and a driver travelled in a vehicle at a speed of 60 km/h along the highway, collecting data 3 days a week, providing primary data complementing the long-term data. The recorded data included: name of the data collector, date, roadkill location, species involved, and carcass duration. Locations of roadkill were recorded using a Global Positioning System (GPS) device. Once documented, carcasses were removed from the roadside to prevent double counting. The roadkill was then categorised into six major groups: domestic animals, reptiles, birds, carnivores, herbivores, and omnivores, and subsequently classified into family, genus, and species. The roadkill that could not be identified or classified was labelled as unknown.

2.2.2 | Environmental Variables

Geographic Information Systems (GIS) techniques were employed to collect data on various geographical and environmental variables, including corners, culverts, fences, surface water, migratory routes, land use and land cover, slope, urban centres, and settlements. Data on rivers, dams, road corners, ranches, and settlements were obtained by digitising points using Google Earth Pro, which were then exported into ArcMap in KML file format for conversion into the respective GIS layers. Information on culverts, migratory routes, and surface water such as stagnant rainwater and seasonal rivers was recorded using a handheld GPS device. Data on fences was collected by recording the GPS coordinates of the two endpoints of each fenced section along the highway, particularly near ranches and proposed government projects. ArcMap was utilised to generate a road buffer of 500 m.

For land-use-land-cover (LULC) data, Landsat TM imagery for 2019 was downloaded from the United States Geological Survey (USGS) Earth Explorer website (http://earthexplorer.usgs.gov/). The imagery was processed to generate a LULC map following five steps as outlined by Kimanzi (2011): image pre-processing, image visual interpretation, ground truthing, digital image classification, and accuracy assessment. Ground truthing for LULC was conducted using a stratified random sampling technique, with points located using a handheld GPS device. The LULC map was generated in ArcMap using the maximum likelihood algorithm, categorising LULC into farmland, open grassland, dwarf shrub grassland, open shrubland, and sparsely vegetated dwarf shrubland. Additionally, a Landsat digital elevation model (DEM) of the area was downloaded from the USGS website. Using ArcMap, a slope map was created from the DEM with a specified set of percentages. Figure 2 illustrates the environmental variables in the form of map layers generated using these GIS techniques.

2.2.3 | Statistical Data Analysis

A total of 408 roadkill sightings were recorded along a 72 km stretch of highway to collect presence data from 2013 to 2018. All roadkill sightings without reference coordinates were excluded. A presence point map for roadkill was generated based on the collected data.

Random absence points (408) were generated using the 'generate random point tool' in ArcMap. These points were then merged with the presence of roadkill locations. The near distance to each roadkill location was calculated for continuous variables, which included surface water, fences, road corners, culverts, migratory routes, and settlements, and the results were exported as pivot tables. For the LULC and slope variables, roadkill points were utilised to extract corresponding values.

Spearman rank correlation (r) and the variance inflation factor (VIF) were employed to assess multicollinearity among the independent variables. Since none of the variables exhibited $r > 0.7$ or VIF > 10, all were considered suitable for logistic regression (Menard 2009). The model's fitness was evaluated using the Nagelkerke R^2 coefficient. To examine the relationship between geographical and environmental factors (independent variables) and roadkill presence/absence (dependent variable), data were analysed using stepwise binary logistic regression in STATGRAPHICS Centurion XVI.I software (Smith and McKenna 2013). Kennel density was utilised to identify roadkill hotspots for the various animal groups.

3 | Results

3.1 | Roadkill Density of Wildlife and Domestic Animal Species Along Kyumvi to Sultan Hamud Highway

From the roadkill occurrences, 51 species from six animal groups (herbivores, carnivores, omnivores, birds, reptiles and domestic animals) were documented with an overall roadkill density of 0.944 roadkill/km/y. The domestic animal group, which includes six species, exhibited the highest roadkill density, with domestic dogs and cats accounting for the most incidents whereas chickens and sheep had the least (Table 1f). Among wildlife, wild herbivores, comprising 13 species, had the highest roadkill density, with the Cape hare experiencing the most incidents, followed by hedgehogs (Table 1b). The common duiker and spring hare recorded the least roadkill occurrences. The second wildlife group, wild carnivores, included 14 species, with the white-tailed mongoose having the highest roadkill incidents, followed by spotted hyenas (Table 1a). Civets and wild dogs had the least roadkill occurrences. The avian group, comprising 12 species, had the pied crow recording the highest number of roadkill incidents, followed by the superb starling, while the secretary bird and black-bellied bustard had the fewest (Table 1d). Reptiles, comprising four species, had the green snake experiencing the most incidents, followed by the puff adder (Table 1e). The striped skink recorded the least roadkill occurrences. The wildlife group with the lowest roadkill incidents was the wild omnivores, which included only two species. Baboons had the highest number of roadkill incidents, while

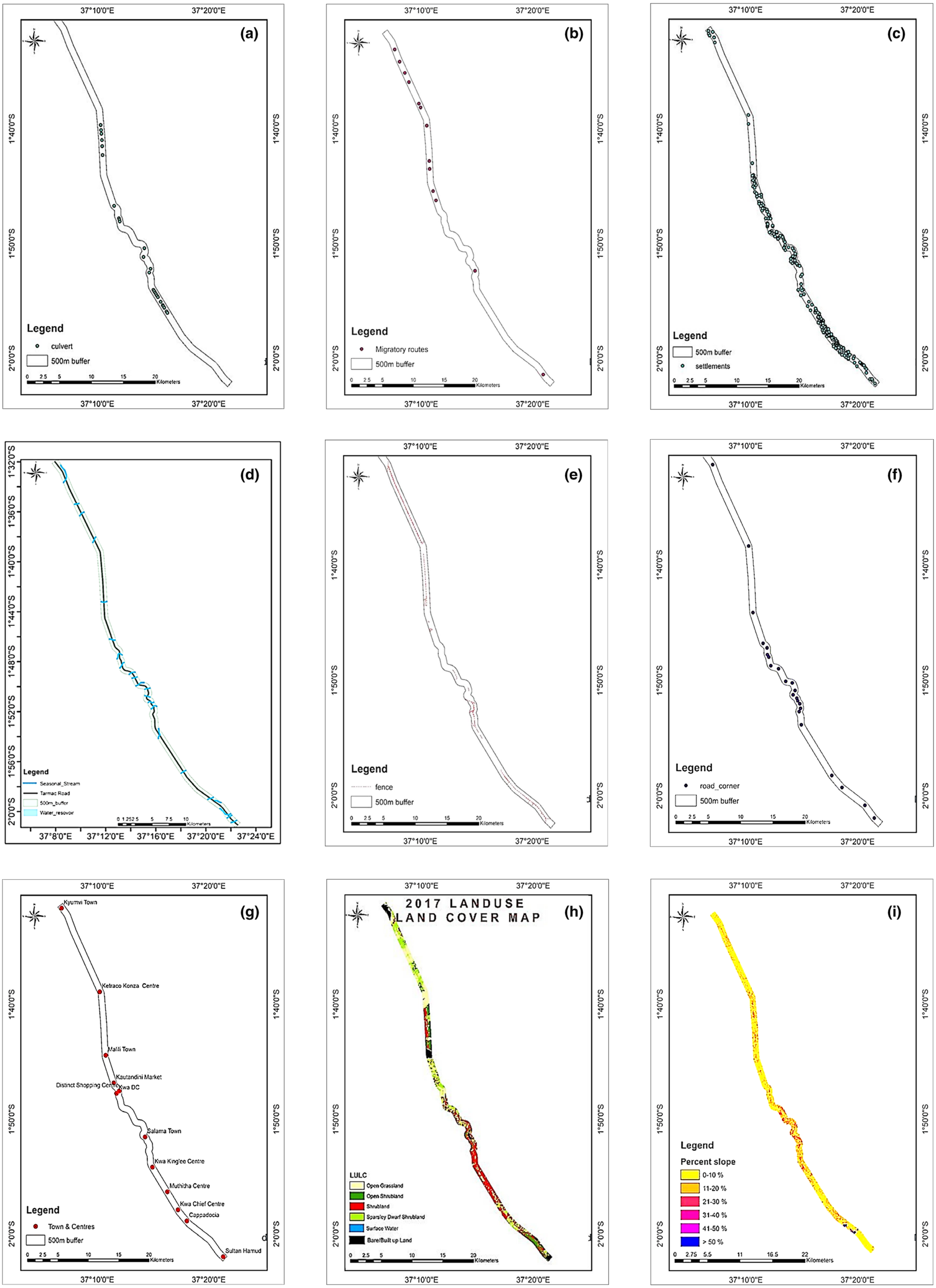

FIGURE 2 | Map layers of environmental variables generated using the GIS techniques.

TABLE 1 | Density of roadkill for (a) Wild carnivores, (b) Wild herbivores, (c) Wild omnivores, (d) Avian species, (e) Reptiles and (f) Domestic animals along the Kyumvi–Sultan Hamud highway stretch from 2013 to 2018.

Species common name (scientific name)	No. of roadkill	Density (roadkill/km/year)
(a) Wild carnivore species		
White-tailed mongoose (*Ichneumia albicauda*)	25	0.058
Spotted hyena (*Crocuta crocuta*)	17	0.039
Genet (*Genetta genetta*)	6	0.014
Silver backed jackal (*Canis aureus*)	7	0.016
Serval cat (*Leptailurus serval*)	4	0.009
Cheetah (*Acinonyx jubatus*)	2	0.005
African civet (*Civettictis civetta*)	2	0.005
Aardwolf (*Proteles cristata*)	1	0.002
Honey badger (*Mllivora capensis*)	1	0.002
Stripped hyena (*Hyaena hyaena*)	1	0.002
Wildcat (*Felis silvestris*)	1	0.002
Wild dog (*Lycaon pictus*)	1	0.002
Total	68	0.157
(b) Wild herbivore species		
Cape hare (*Lepus capensis*)	27	0.063
Hedgehog (*Atelerix albiventris*)	14	0.032
Kongoni (*Alcelaphus buselaphus*)	8	0.019
Dik dik (*Madoqua kirkii*)	7	0.016
Wildebeest (*Connochaetes gnou*)	7	0.016
Common zebra (*Equus equus*)	7	0.016
Eland (*Taurotragus oryx pattersonianus*)	4	0.009
Thomson gazelle (*Eudocars thomsonii*)	4	0.009

(Continues)

TABLE 1 | (Continued)

Species common name (scientific name)	No. of roadkill	Density (roadkill/km/year)
Cape buffalo (*Syncerus caffe caffer*)	3	0.007
Crested porcupine (*Hystrix cristata*)	3	0.007
Ground squirrel (*Xerus rutilus*)	2	0.005
Common duiker (*Sylvicapra grimmia*)	1	0.002
Spring hare (*Pedetes capensis*)	1	0.002
Total	88	0.204
(c) Wild omnivores species		
Baboon (*Papio ursinus*)	5	0.012
Bat-eared fox (*Otocyon megalotis*)	1	0.002
Total	6	0.014
(d) Avian species		
Pied crow (*Corvus albus*)	10	0.023
Superb starling (*Lamprotornis superbus*)	8	0.019
Baglafetch weaver (*Ploceus baglafecth*)	5	0.012
Masked weaver (*Ploceus velatus*)	4	0.009
White- bellies bustard (*Eupodotis senegalensis*)	3	0.007
Sparrow weaver (*Plocpasser mahali*)	2	0.005
Village weaver (*Ploceus cucullatus*)	2	0.005
Black–bellied bustard (*Lissitis melanogaster*)	1	0.002
Black- shouldered kite (*Elanus axillaris*)	1	0.002
Mouse bird (*Urocolius macrourus*)	1	0.002
Secretary bird (*Sagittarius serpentarius*)	1	0.002
Yellow bishop (*Euplectes capensis*)	1	0.002
Total	39	0.090

(Continues)

TABLE 1 | (Continued)

Species common name (scientific name)	No. of roadkill	Density (roadkill/km/year)
(e) Reptile species		
Green snake (*Philothamnus sp*)	5	0.012
Puff adder (*Bitis arietans*)	4	0.009
Rock python (*Python sebae*)	1	0.002
Stripped skink (*Mabuya striata*)	1	0.002
Total	11	0.025
(f) Domestic species		
Domestic dog (*Canis lupus familiaris*)	153	0.354
Domestic cat (*Felis silvestris catus*)	32	0.074
Cattle (*Bos taurus*)	2	0.005
Goat (*Capra aegagrus hircus*)	2	0.005
Chicken (*Gallus domesticus*)	1	0.002
Sheep (*Ovis aries*)	1	0.002
Total	191	0.442
(g) Unknown species		
Unknown species	5	0.012
Total	5	0.012

bat-eared foxes had the fewest (Table 1c). Lastly, there were instances of unknown species, which had a roadkill density of 0.012 roadkill/km/y (Table 1g).

3.2 | Factors Influencing Wild and Domestic Animal Roadkill Along Kyumvi to Sultan Hamud Highway

A logistic regression model was employed to examine the probability of roadkill occurrence and random points along the Kyumvi to Sultan Hamud highway. This analysis considered continuous variables (distance to culverts, migratory routes, settlements, road corners, fences, water sources, and slope) and categorical factors (land use and land cover). The model was applied separately to five animal categories: all animal species, wild birds, wild herbivores, domestic animals, and wild carnivores. Due to insufficient data, logistic regression was not conducted for wild omnivores and reptiles.

3.2.1 | Roadkill Analysis for All Animal Species

From the binary logistic regression analysis, the final model identified six covariates that were statistically significant for all roadkill species: distance to migratory routes (Dmigratoryroute), settlement (Dsettlement), culverts (Dculvert), corners (Dcorner), fences (Dfence), and land cover types (grassland, dwarf shrub grassland, and open shrubland) (Table 2). Migratory routes, culverts, and corners exhibited a negative influence, indicating that areas near these three factors experienced higher rates of roadkill. In contrast, settlement, fences, grassland, dwarf shrub grassland, and open shrubland demonstrated a positive influence, implying that areas near these five factors had lower rates of roadkill. Based on the magnitude of the regression coefficients, open shrubland ($\beta = 0.8562$) had the most substantial impact on the probability of roadkill occurrence, followed by dwarf shrubland ($\beta = 0.7529$) and grassland ($\beta = 0.2454$).

TABLE 2 | Logistic regression estimates for all animal species.

Parameter	Coefficient (β)	Standard error	Df	p
Dmigratoryroute	−0.00008	0.00004	1	0.0332
Dsettlement	0.00037	0.00015	1	0.0106
Dculvert	−0.00018	0.00003	1	0.0001
Dcorner	−0.00028	0.00010	1	0.0043
Dfence	0.00018	0.00008	1	0.0229
Dwarf shrub	0.75290	0.31237	11	0.0108
Grassland	0.24540	0.24510	1	0.0038
Open shrub land	0.85620	0.24320	1	0.0210

3.2.2 | Roadkill Incidents Involving Avian Species

The final logistic model identified four statistically significant covariates in areas with ranches, (grasslands, dwarf shrub grasslands, and open shrublands) related to avian roadkill (Table 3). Ranches, grasslands, and open shrublands exhibited a positive influence on the occurrence of avian roadkill, whereas dwarf shrub grasslands demonstrated a negative influence.

3.2.3 | Analysis of Roadkill Incidents Involving Herbivores

Factors influencing wild herbivorous roadkill include the distances to culverts, migratory corridors, and land cover types (grassland, dwarf shrub grassland, and open shrubland) (see Table 4). The distance to culverts and migratory routes had a negative impact, while all the land cover types positively influenced wild herbivore roadkill. The goodness of fit for this logistic model was strong, as indicated by the likelihood ratio test ($\chi^2 = 48.1591$, df $= 5$, $p = 0.0001$).

3.2.4 | Analysis of Roadkill Involving Domestic Animals

The covariates that were statistically significant for domestic animals in the binary logistic regression model included: distances

TABLE 3 | Factors determining avian roadkill derived from binary logistic regression.

Parameter	Coefficient (β)	Standard error	Df	p
Ranch	0.00014	0.00007	1	0.0164
Grassland	1.89861	0.00001	11	0.0034
Dwarf shrub grassland	−0.61920	0.00002	1	< 0.0001
Open shrub land	0.06976	0.00013	1	< 0.0001

TABLE 4 | Factors determining domestic animals' roadkill.

Parameter	Coefficient (β)	Standard error	Df	p
Dculvert	−0.00046	0.00012	1	0.0001
Dmigratoryroute	−0.00036	0.00012	1	0.0015
Grassland	2.36826	0.90994	1	0.0013
Dwarf shrub grassland	0.51610	0.04032	1	< 0.0001
Open Shrub land	2.16419	0.08144	1	< 0.0001

TABLE 5 | Factors determining domestic animals' roadkill.

Parameter	Coefficient (β)	Standard error	Df	p
Dmigratoryroute	−0.00015	0.00006	1	0.0122
Dsettelment	−0.00070	0.00038	1	0.0317
Dculvert	−0.00015	0.00003	1	0.0001
Durban	−0.00022	0.00009	1	0.0075

TABLE 6 | Factors determining wild carnivore roadkill.

Parameter	Coefficient (β)	Standard error	Df	p
Dculvert	−0.00044	0.00011	1	0.0001
Dcorner	−0.00088	0.00023	1	0.0001
RanchR	0.00029	0.00009	1	0.0006
Grassland	1.80025	0.82574	1	0.0004
Dwarf shrub grassland	0.58280	0.91123	1	0.0001
Open shrub land	1.056760	1.05464	1	0.0001

to migratory routes, settlements, culverts, and towns and urban centres (Table 5). All four factors exhibited a negative influence on domestic animal roadkill. The likelihood ratio test from the logistic regression for domestic animal roadkill indicated a good model fit ($\chi^2 = 82.492$, df = 4, $p < 0.0001$).

3.2.5 | Analysis of Roadkill Incidents Involving Wild Carnivorous Mammals

The covariates that were statistically significant for roadkill involving wild carnivores included: distances to culverts and road corners having a negative influence—increasing frequency of collisions, while ranches and land cover types (grassland, dwarf shrub grassland, and open shrubland) decreased roadkill numbers (Table 6). The likelihood ratio test of the logistic model for wild carnivores' roadkill indicated a good fit ($\chi^2 = 53.8348$, df = 6, $p < 0.0001$).

3.3 | Animal Roadkill Hotspots Along the Kyumvi to Sultan Hamud Highway

To determine the locations of roadkill incidents, a kernel density hotspot analysis was conducted for all species combined, as well as for various animal groups separately, to create a continuous field of hotspots (Figure 3). These hotspots were generated using the final best model, which included only the significant factors.

In general, most animal hotspots were located between Ketraco Konza and Salama towns, but specific hotspot locations varied among different animal groups. For all animal species (Figure 3a) and herbivores (Figure 3b), the majority of roadkill incidents occurred from Ketraco Konza town to just beyond Kwa DC town. For domestic animals (Figure 3c), most incidents were reported between Malili and Salama towns. For Aves (Figure 3d), most roadkill incidents were recorded between Ketraco and Salama towns. For carnivores (Figure 3e), the majority of roadkill occurred around Ketraco and between Malili and Salama towns.

4 | Discussion

4.1 | Roadkill Density of Animal Species Along Kyumvi to Sultan Hamud Highway

An overall animal roadkill density of 0.944 roadkill/km/year recorded along the 72 km stretch of the Kyumvi to Sultan Hamud highway could translate to approximately 500 animals per year for the entire highway length from Nairobi to Mombasa. This figure may adversely impact vulnerable, threatened, or endangered wildlife species, particularly in expansive, unfenced protected areas such as Tsavo National Park. The roadkill incidents affected 51 species across six animal groups: herbivores, carnivores, omnivores, birds, reptiles, and domestic animals. Among the affected groups, domestic animals, especially dogs and cats, are notably the most frequently killed. Their foraging behaviour, as noted by Schwartz et al. (2018), leads them to scavenge along roadsides, putting them in harm's way. This situation highlights not only the direct impact of road infrastructure but also the indirect consequences arising from human settlements adjacent to these roads. Fedriani et al. (2001) provided insights into the potential impacts of anthropogenic factors on wildlife

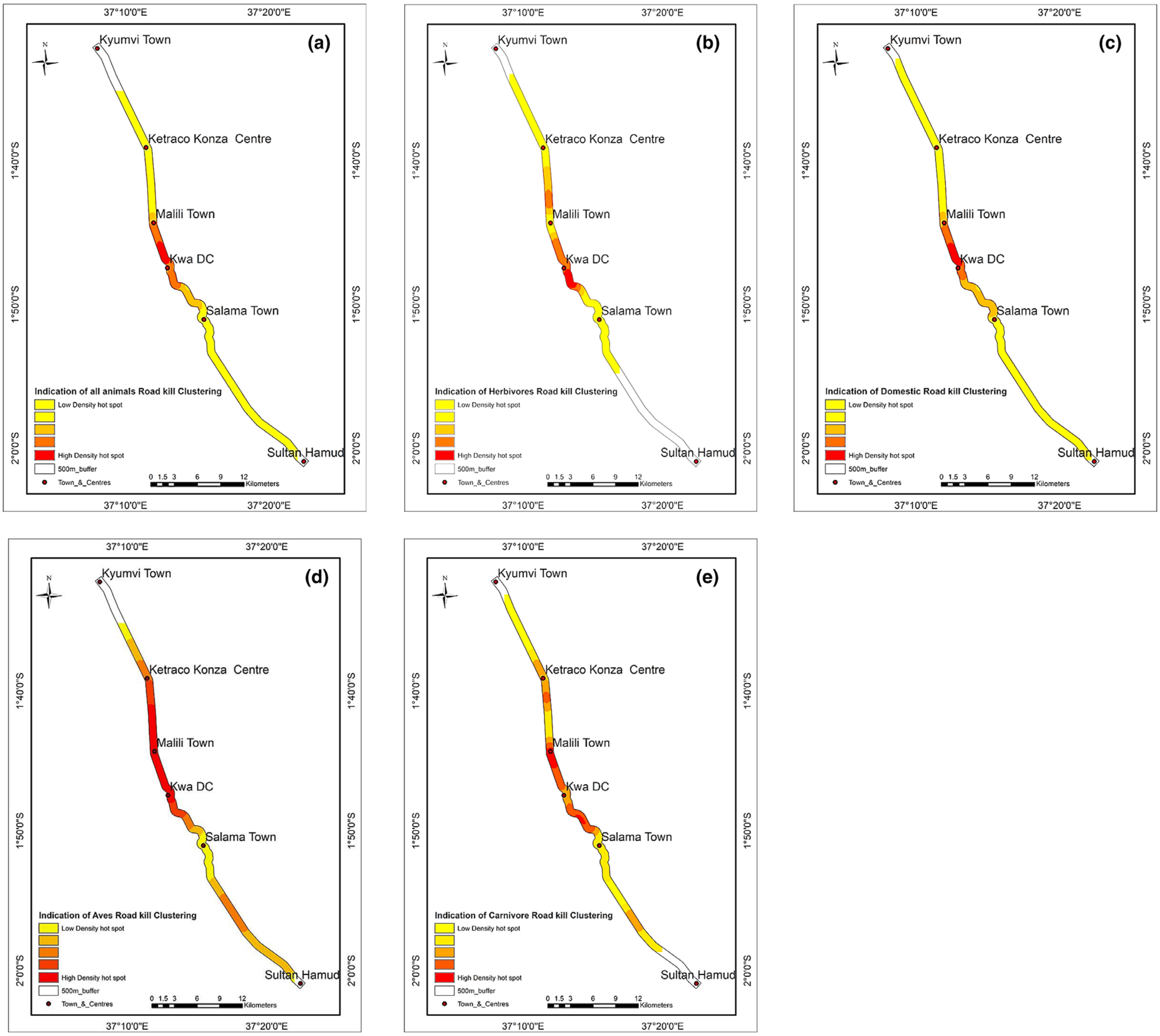

FIGURE 3 | Roadkill hotspots along Kyumvi to Sultan Hamud highway for (a) all species, (b) herbivores, (c) domestic animals, (d) aves and (e) carnivores.

populations. The study emphasises how human activities, like providing food sources near roads, can alter animal behaviour and increase the risk of collisions with vehicles, as observed along the NMH, where the transport industry has fostered an environment conducive to the proliferation of hotels. Wild herbivores, such as Cape hares and hedgehogs, also suffer significant casualties due to their behavioural patterns. Cape hares, known for crossing roads directly in front of vehicles (Zaman et al. 2020), are particularly vulnerable. Similarly, hedgehogs' instinct to curl up and remain motionless in response to threats (Haigh 2011) heightens their likelihood of being struck by vehicles. The impact on wild carnivores, such as white-tailed mongooses and spotted hyenas, underscores the cascading effects of roadkill on ecosystems. Collinson (2013) highlights the extensive foraging and scavenging behaviour of these species, which exposes them to roadkill carcasses and subsequent collisions with vehicles. Birds, exemplified by the pied crow, are also affected by their scavenging behaviour on roadkill carcasses. This situation underscores the interconnectedness of species and the indirect effects of road infrastructure on wildlife dynamics. Even omnivores, such as baboons, are not exempt from the threat of roadkill. Their tendency to forage along roadsides, particularly for squashed insects, increases their risk of collision with vehicles (Kitchell Jr. 2014). Reptiles, including green snakes and puff adders, face similar risks, as their behaviour patterns predispose them to vehicle collisions. Puff adders, in particular, are active shortly after sunset and predominantly remain on the ground, making them vulnerable to oncoming traffic.

Kreling et al. (2019) highlight that roadkill densities result from increasing human-wildlife conflict at the wildland-urban interface, where natural habitats intersect with human development. This study provides valuable insights into the environmental and anthropogenic factors influencing roadkill distribution in these critical areas.

4.2 | Factors Determining Animal Roadkill Along Kyumvi to Sultan Hamud Highway

Results from the logistic regression showed that for all animal species, roadkill incidents were higher in areas near migratory routes, corners, and culverts, but lower in regions adjacent to settlements, fences, grasslands, dwarf shrub grasslands, and open shrublands. The high incidence of roadkill can be attributed to the numerous wild animals using migratory routes to cross the highway. According to Gonser et al. (2009), roadkill has a significantly higher probability of occurring in areas where the habitat provides attractive resources for wildlife that are absent in their surroundings. Limited visibility for both drivers and animals at road corners contributed to the increased roadkill. Although culverts were expected to reduce animal roadkill, the opposite effect was observed, possibly due to blockages or poor design of the existing culverts along the highway. Settlements tend to displace wild animals, thereby reducing roadkill incidents. Fences deter animals from accessing the highway, further decreasing the likelihood of roadkill. The open habitats, including grasslands, dwarf shrub grasslands, and open shrublands, provided drivers with better visibility, which consequently reduced roadkill occurrences. Jakobsson et al. (2018) noted that animal-vehicle collisions are diminished by open vegetation coverage but are increased by the presence of migratory corridors. Hobday and Minstrell (2008) identified various natural factors contributing to roadkill, including animal density in the area, the presence of forage along the roads that attract animals, and migratory corridors. Clevenger et al. (2003) and Eberhardt et al. (2013) indicated that road sections with dense vegetative cover are potential hotspots for roadkill.

Roadkill among different animal groups is influenced by a variety of factors, primarily due to differences in foraging behaviour. Wild carnivore roadkill is more prevalent near culverts and corners, while it is less common in open habitats and ranches, where fences deter animals from accessing the highway. In contrast, roadkill of domestic animals occurs more frequently near settlements, urban centres, culverts, and migratory routes. The high density of domestic animals in settlements and urban areas contributes to this increased roadkill. For instance, dogs are known to roam around these areas in search of food and often scavenge carcasses along the roads (Schwartz et al. 2018), which further elevates their risk of vehicle collisions. A study by Sadleir and Linklater (2016) examined annual and seasonal patterns in wildlife roadkill and their relationship with traffic density. The research emphasised that roadkill is not random; it is influenced by species traits, movements, microhabitat use, and thermal strategies. Larger, slow-moving species are more vulnerable to vehicle collisions compared to their smaller, faster counterparts. Additionally, the study provided valuable insights into the annual and seasonal patterns of wildlife roadkill and its correlation with factors affecting animal-vehicle collisions. The findings highlight the significant impact of road networks on wildlife mortality, underscoring the need for effective mitigation strategies to reduce roadkill rates.

4.3 | Animal Roadkill Hotspots Along Kyumvi to Sultan Hamud Highway

For mapping purposes, the study employed kernel density hotspot analysis to identify areas with a high probability of roadkill occurrences. Roadkill hotspots for most animal groups along the highway were found between Ketraco Konza Centre and Salama Town; however, specific hotspot locations varied among different animal groups. These groups differences were not significant enough to warrant separate discussion. This stretch of the highway is characterised by numerous corners, migratory routes, steep slopes, settlements, surface water, and a lack of fencing. These factors contributed to the location of roadkill hotspots for various animal groups. The numerous corners reduced visibility for drivers, resulting in increased roadkill incidents. The concentration of migratory routes for various wildlife also contributed to the high rates of roadkill. Favilli et al. (2018) found that patchy habitats coinciding with infrastructure corridors pose a significant collision risk. Additionally, the road structure in this NMH stretch has few physical mechanisms to control speed; there are speed bumps only at the entry and exit points of each town, along with downhill stretches that feature sharp bends due to the hilly terrain. de Resende Assis et al. (2022) assert that downhill stretches of roads allow vehicles to travel at high speeds, contributing to the highest incidence of roadkill. The numerous settlements and urban centres between Ketraco Konza Centre and Salama Town harbour many domestic animals, which contribute significantly to roadkill rates. A study by Hui et al. (2021) noted that roadkill incidents were highest on roads passing through villages. The presence of surface water bodies along this highway stretch attracted many animals, leading to increased roadkill. Previous roadkill studies have shown that roads near wetlands and ponds are likely to experience higher roadkill rates (Furness and Soluk 2015), as are artificial waterholes near roads (Kioko et al. 2015) and roads crossing drainage lines (Saeki and Macdonald 2004). The absence of fencing in this NMH stretch allowed unrestricted access for all animals to the highway, further contributing to the high rates of roadkill.

4.4 | Implications for Wildlife Conservation Along Nairobi–Mombasa Highway (NMH)

The study identified several factors influencing wildlife and domestic roadkill along the NMH. Disrupted migration routes, road corners, culverts, settlements, and urban centres were found to significantly increase the incidence of animal roadkill. This finding aligns with the research conducted by Moore et al. (2023), which demonstrated that roads intersecting critical wildlife migration routes lead to higher mortality rates among migrating species. Similarly, Oddone-Aquino and Nkomo (2021) and Dean et al. (2019) noted that road corners and culverts, often associated with poor visibility and abrupt changes in terrain, contribute to an increase in wildlife-vehicle collisions.

Conversely, fences, ranches, settlements, and open vegetation (grassland, dwarf shrub grassland, and open shrubland) were associated with a reduction in roadkill. This finding supports the research conducted by Keken et al. (2019) and Mayer et al. (2021), which indicated that areas with clear visibility, such as open vegetation zones, enable both drivers and animals to detect each other earlier, thereby reducing the risk of collisions. Additionally, the presence of fences along highways, as noted in this study, was also highlighted by Huijser et al. (2021) as an effective measure for directing wildlife away from roads, thus preventing roadkill.

Our research suggests several strategies for road planners and researchers that are supported by previous studies. Restoring and protecting blocked migration corridors is crucial for keeping wildlife off highways as echoed by Keken et al. (2019) and Mayer et al. (2021). Additionally, installing speed bumps or enforcing speed limits in areas with poor visibility, such as road corners, can help mitigate animal-vehicle collisions, as recommended by Hilty et al. (2019). Furthermore, proper signage at animal crossings and habitats is essential. This strategy is supported by Thela (2022), who emphasised the importance of clear signage in reducing roadkill incidents in areas with high domestic animal density. The study also emphasises the importance of maintaining culverts and underpasses, particularly during the rainy season, a period when these structures are susceptible to clogging. The Economic and Social Survey of Asia and the Pacific (2017) demonstrated that well-maintained culverts can function as effective wildlife passage routes, converting them from barriers into safe corridors for animals.

The inclusion of roadkill records, wildlife atlases, and various data sampling methods is essential for identifying species sensitive to fragmentation and critical collision hotspots (Zheng et al. 2024). Roadkill records offer a longitudinal dataset that reveals trends in roadkill, while wildlife atlases provide vital insights into species distribution and habitat connectivity (Rytwinski et al. 2016; Acharya 2022). Furthermore, diverse data sampling techniques, such as carcass surveys, camera traps, and GPS tracking, offer complementary perspectives that enhance our understanding of roadkill dynamics and inform more targeted conservation efforts. This approach is particularly crucial for studying fragmentation-sensitive species, which are more vulnerable to the disruptive effects of roads due to their specific habitat requirements and movement patterns, as discussed by Bennett (2017).

For the effective management of roadkill and sustainable wildlife conservation, it is crucial to coordinate the construction of wildlife and livestock underpasses and overpasses with identified collision hotspots. Studies by Goldingay et al. (2022) have demonstrated that properly designed and maintained passage routes significantly reduce roadkill incidents. Collaboration with experts in linear ecology and thorough research on potential crossing sites are key to ensuring the success of these measures. Furthermore, establishing a national road monitoring network to systematically gather data on wildlife-vehicle collisions, as proposed by Rytwinski et al. (2016), will aid in the long-term control of roadkill.

Regarding wildlife conservation, areas surrounding settlements, which often displace wild animals, may require less intervention. Establishing fences along highways and ranches, which are often fenced and well-managed, has been found to contribute to a decrease in roadkill incidents (Bissonette and Rosa 2009). Also, maintaining a clear zone of open vegetation alongside roads, which promotes good visibility for both drivers and animals, can further minimise collisions and support conservation efforts, as highlighted by Lala et al. (2021).

This study, which focused on just 14% of the total NMH, should be expanded to other sections of the highway to account for varying conservation practices, environmental conditions, and roadkill patterns. This expansion is especially critical in biodiversity-rich areas like Tsavo, where understanding roadkill patterns can inform more effective conservation strategies. The insights gained from this study should be applied to other roads in Kenya and considered in future infrastructure projects. By doing so, we can more effectively manage and reduce the threat of roadkill, ensuring the sustainable conservation of wildlife across Kenya and the broader East African region (Seto et al. 2016; Bennett 2017).

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data can be obtained from the corresponding author upon request.

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