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DOES THE GEOMETRICAL DESIGN OF ROADS INFLUENCE WILDLIFE ROADKILLS? EVIDENCE FROM A HIGHWAY IN CENTRAL ANDES OF COLOMBIA

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Abstract.

The highway infrastructures are a source of multiple environmental problems; one of the worst effects on wildlife is roadkill. Most of the research on roadkill has focused on how certain aspects, such as seasons, traffic density, and location of roadways, among others affect wildlife mortality on roads. However, little attention has been paid to understanding how the geometric design of roads affects wildlife mortality. On a highway in the Central Andes of Colombia, we investigated if the geometric design, specifically horizontal alignment and vertical curves of the road, influence the mortality of vertebrate animals on roadways. We determined the number of the straight lines, circular, transition curves, and vertical convex curves along the entire route of the highway (13.9 km), and from April 2018 to December 2019, we made 336 surveys in search of wildlife roadkill. We then investigated the relation of animal deaths to different road shapes. Out of 95 roadkill, reptile deaths made up 47% of the total. We found no dependence on the distribution of deaths by class of animals on the road shape; the shape in which most deaths occurred was a straight line (58 deaths). However, when the proportion of mortality events per meter was analysed on the shape units on the road, we found that circular and transition curves presented two and three times (respectively) a higher proportion of mortality events per meter than the straight lines. Roadkill hotspots were found in curved segments and were not associated only with riparian forest. The curved sections present more dangerous geometric designs than the straight lines for wildlife, regardless of their length on the road. Our research indicates that the relationship of the geometric design of roads needs to be considered in the development of management and conservation plans of altered ecosystems with the road infrastructure.

Key words: Ecology roads; Geometrical design of roads; Wildlife roadkills; Roadkill hotspots.

Introduction

Terrestrial transportation is a result of the rapid development of cities and population growth, since the highways are an important connection source for social and economic relations (Freeman 1995; Coffin 2007; Arévalo et al., 2017). However, road infrastructure also has negative environmental impacts, i.e., the habitat loss, vegetal cover fragmentation (Spellerberg 1998; Geneletti 2003; Jaeger et al., 2005), edge effects and dispersion of populations (Arévalo et al., 2017; Oxley et al., 1974; Holderegger & Giulio 2010), but of all, wildlife roadkill is the most conspicuous impact. Several studies have shown how local biodiversity is reduced by the presence of roads/highways (Fahrig et al., 1995; Jaeger et al., 2005; Marsh et al., 2008; Holderegger & Giulio 2010; Berthinussen & Altringham 2012).

Roads have been developed to supply the human need for moving and traveling (Arévalo et al., 2017). With more people driving every day, roads have been designed wider, with more lanes, higher speeds, and continuous operation, always adjusting their outline to the characteristics of the terrain on which they are traced (Forman 2004; Invías 2008). Geometric design is used to relate the form of a road within the frame of a landscape and is also used to promote the reduction of accident risk (Comte & Jamson 2000; Invías 2008). Currently, the design of some roads take into account wildlife crossings (Delgado-Vélez 2014), which are not suitable for all species (Dodd et al., 2004). Although the geometric design promotes the safest conditions for human transportation, it does not conform to the behaviour of animal vertebrates, since animals do not react similarly to stressful conditions, such as the arrival of high-speed vehicles, high-traffic lanes, blind spots on the route, and the sudden appearance of a vehicle (Lee et al., 2004; Abrahms et al., 2016; Cappa et al., 2017).

Most of the research on roadkill has focused on the number of animals hit by cars on different connected roads (Rodda 1990; Ashley & Robinson 1996; Bager & Da Rosa 2011; De La Ossa & Galván-Guevara 2015), on the spatio-temporal occurrence of roadkill of different species (Alvez da Rosa & Bager 2012; Arévalo et al., 2017), the effect of roadkill on population density (Reijnen & Foppen 1995; Bennett 2017) and also, the manner in which some animal species behave in order to bypass a highway (Goosem 2001; Gavin & Komers 2006; Abrahms et al., 2016; Cappa et al., 2017). However, there has been little research on understanding whether the form of road infrastructure increases wildlife roadkill (Lee et al., 2004; Dodd et al., 2004; Jaeger et al., 2005). As such, every study addressing the effects of highways on biological diversity makes an important contribution when considering management strategies for ecosystem conservation (Forman 2004; Coffin 2007; Bager & Da Rosa 2011; Bennett 2017). Therefore, the objective of our investigation was to determine if the geometrical design of the road, specifically horizontal alignments and the vertical convex curves affects wildlife roadkill on a highway in the Central Andes of Colombia.

Materials and Methods

The study area was the 13.9 km of highway from the municipality of San Jerónimo (6°26’32.7” N, 75°43’57.6” W. In this study, we will mark the beginning of the highway studied, kilometre zero, (K)0+000 and its end 13+900) to the bridge at the main entrance to Santa Fe de Antioquia (6°30’44.8” N, 75°49’04.6” W, 12+900 kilometres), Antioquia Department, Central Andes of Colombia; the route is part of the Highway to the Sea, which connects the city of Medellín with the Pacific Gulf of Antioquia (Cortes 2012, Fig. 1). The altitudinal range varies from 465 to 719 meters above sea level, with an average temperature of 27 °C (Cortes 2012; Osorio 2016). This route is composed of two lanes, with no signs for the protection of wildlife, with a maximum permitted speed of 80 km/h, and in some sections, there are posted speed reduction signals. The area surrounding the highway is, according to Holdrige (1978), a tropical dry forest with two quite marked dry seasons extending from December to March and June to July (Osorio 2016), with many green spaces, often with pastureland adjacent to the road (Cortes 2012; Osorio 2016). On the right side of the highway is the Aurrá River, which flows to the Cauca River at 12+000 kilometres.

Road mortality data: From April 2018 to December 2019, we carried out surveys for 4 days per week (round trip) for a total of 336 survey routes, on a motorcycle at a maximum speed of 30 km/h. The surveys were conducted by motorcycle rather than by car or walking since (1) the frame of cars do not allow a clear visibility of animal carcasses at the edges of the road; and (2) walking requires a greater number of hours and / or people for sampling. All vertebrate wildlife deaths on the road were georeferenced using a GPS (Global Positioning System, Garmin 64SC, expected accuracy 3–5 m, https://www.garmin.com.co/GPSMAP-64SC). A photograph of every individual was taken (when possible, all animals were identified to genus-species taxonomic level); furthermore, each carcass was removed from the highway

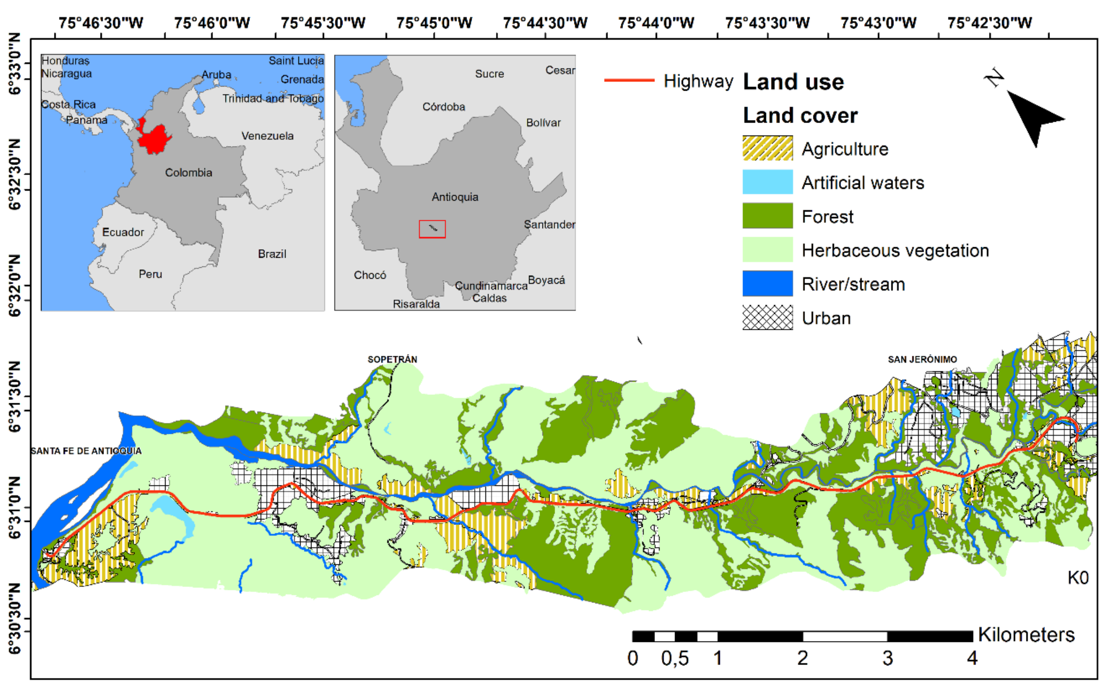

Figure 1: Location of the study area, 13.9 km of highway from San Jerónimo to the bridge of Santa Fe de Antioquia, in the Central Andes of Colombia, showing the watercourses (river/stream) and main land cover.

and buried near the place where it was found, to avoid repeat counting on subsequent surveys (Parra & Rincón 2016).

The shape of the road: To determine the shape of the road, we used aerial images on Google Earth (https://www.google.com/intl/es/earth), along with critical examination in the field. Using GPS tracks and waypoints, we obtained the altitude of every square meter of the road. We identified the features that limit the linear runs of the highway in a horizontal alignment, following the instructions for the geometrical design of roads in Colombia (Invías 2008); these are the straight alignment (straight line on the road), and curved alignments which divide into (1) circular curves and (2) transitional curves.

1. **Circular curves:** The path joining two horizontal consecutive tangents can be constituted by a basic intersection or by the combination of two or more intersections (Invías 2008). We calculate the circular curves by first determining the Arc radius, having the chord of it (the road), with the following equation:

$$r = (a^2 + b^2) / (2*a)$$

Where, **r** = radius, **a** = height from the chord to the edge (tangent) of the arch, and **b** = half of the length of the arc chord (Cad-Projects http://www.cad-projects.org; Fig. 2-I). With the radius determined, it was possible to draw the circular curve.

2. **Transition curves:** Curves of variable degree of curvature that allow a smooth transition when going from straight alignments to circular curves or vice versa or also between two circular curves (Invías 2008); obtained by the following equation:

$$A^2 = L*R; \; L = R*2\theta$$

Where, **A** (parameter) when setting the spiral size = sets the relationship between **R** = radius, **L** = length of the transition curve, and θ = central angle of the spiral (Cad-Projects http://www.cad-projects.org; Fig. 2-II).

Then, we identified the vertical curves that link two consecutive tangents of the vertical alignment, which through the gradual passage of the slope of the input tangent to that of the output tangent can reduce or prevent visibility of roadway ahead, according to the degree of incline of their slope (Invías 2008; Ziliongiene & Vorobjovas 2011). Specifically, the length of the crest curve, which relates to the stopping sight distance calculated by the equation:

$$L = \frac{A.S^2}{100.(\sqrt{2.h_1} + \sqrt{2.h_2})}; \text{ when } S \leq L$$

Where: **L** = length of crest vertical curve, **S** = sight distance, **A** = difference in the gradients of vertical tangents (**A** = $|G_2\text{-}G_1|$), $\mathbf{G_1}$, $\mathbf{G_2}$ = gradients of vertical tangents (%), $\mathbf{h_1}$ = height of the driver's eyes (for a visible stopping distance of 1 m, for a passing sight distance of 1 m), $\mathbf{h_2}$ = height of obstacle on the road (for a visible stopping distance 0.15 m, for a passing sight distance of 1.2 m; Ziliongiene & Vorobjovas 2011; Fig. 2-III).

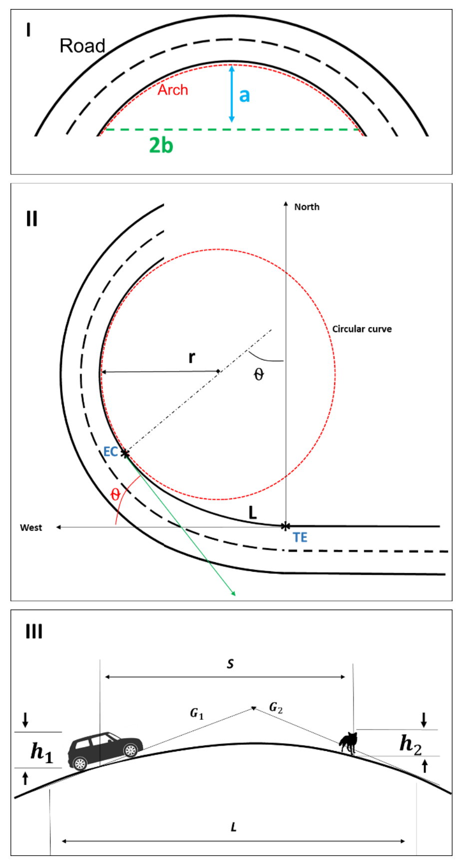

Figure 2: I. Arch of a circle, a = height of chord, 2b = chord length. **II.** Transition curve, r = radius of the circular curve, L = transition curve length, θ = Deflection angle of the circular curve, θ = Deflection angle of the spiral, TE = splice of the straight line and transition curve, TC = intersection between the transition curve and circular curve, green arrow = External splice bisector. **III.** Length of vertical curve, S = Sight distance, L = Vertical curve length, G_1, G_2 = gradient of vertical tangents (%), h_1 = height of driver's eyes, h_2 = height of obstacle.

Table 1. Number of units by road shapes and their descriptive values of length (m), for the highway San Jerónimo to the bridge of Santa Fe de Antioquia, in the Central Andes of Colombia.

		Descriptive values for shape lengths in meters				
Road Shape	**n**	**Min**	**Max**	**Sum**	**Mean**	**Roadkills**
Straight line	36	30.12	705.03	8189.21	227.48	58
Transition curve	85	10.41	108.1	3206.88	37.73	20
Circular curve	43	22.76	344.66	2513.61	58.46	17
Vertical convex curve	3	31	81	164	54.66	0

Note: As we only found three vertical curves with a shorter sight distance than the crestal length, these were (1) K1+800 (6°26’51.9” N, 75°44’27.3” W); (2) K2+600 (6°27’24.9” N, 75°45’12.7” W) and (3) K6+800 (6°28’29.4” N, 75°46’25.1” W), and none of these curves had animal deaths, for this reason these were excluded from the comparison

In total, we determined 36 units of straight lines with a length of 8,189.209 m; 85 units of transition curves with a length of 3,206.88 m; 43 circular curve units with a length of 2,513.61 m, corresponding to the horizontal alignment; and three vertical convex curves units with a length of 164 m, corresponding to the vertical alignment (Table 1).

Relating highway shape with roadkills: Each road shape was subdivided into the units of straight line, transition curve, circular curve and vertical curve, and the distance in meters of each unit was measured. Every roadkill record was attached to the precise location on the road where it occurred, in the vertical and horizontal alignment. From this, we related the number of deaths by route shape and class of animals, and we used a Chi-square analysis to determine if the distribution of animals by class was dependent on the shape of the road (Zhang et al., 2020).

Next, the proportion of mortality events per meter of road shape was determined, dividing the number of deaths for each shape unit by the length of the unit (in meters, thus, it was controlled by size). Then, we used a non-parametric Kruskal-Wallis analysis and a post hoc analysis (Dunn’s test) to determine if there were differences in the proportion of mortality events per meter among the road shapes and how the shape groups varied (Dinno 2017). All analyses were performed in free R software, version 4.0.0 (R Development Core Team 2020).

We conducted a cluster analysis of roadkilled animals to identify roadkill hotspots (Magioli et al., 2019), using the ‘Siriema’ software (Coelho et al., 2014). First, we used the 2-D Ripley’s K statistic, which identifies non-random spatial distribution of roadkilled animals through multiple scales (Coelho et al., 2008) and which takes the sinuosity of the road into account (Magioli et al., 2019). Afterwards, a 2-D Hotspots analysis was carried out using the following parameters: radius = 70 m, number of simulations = 1,000, confidence interval = 95%, for a random distribution of the roadkill locations (Magioli et al., 2019).

To identify if roadkill hotspots were associated to forest corridors or watercourses, since these are common wildlife crossings (Bueno et al., 2013; de Freitas et al., 2015; Magioli et al., 2019), we manually performed a classification of the landscape surrounding the highway, using ArcGIS 10.0 software (ESRI 2012), with aerial images from Google Earth and the land cover of the department of Antioquia (Free download at https://sigot.igac.gov.co/), also comparing with observations in the field (de Freitas et al., 2015). We classified four characteristics of the landscape: agriculture (with grasslands), forest, herbaceous vegetation and urban areas (urban, rural and material exploitation areas); we also measured the distance to the nearest watercourse (river/stream; Bueno et al., 2013), taking into account covers surrounding the roadkill hotspots up to 300 m.

Results

The results were as follows: 95 carcasses were found on the highway, 30.53% corresponded to mammals, 17.8% to birds, 47.3% to reptiles and only 4.2% to amphibians (Table 2). Of these, 94 of the animals were identified up to the genus-species taxonomic level, and there was 1 overly decomposed carcass that could not be identified, one bird (N/A; Table 2). We found no significant differences in the distribution of animal classes by road shape (*Chi-square* = 4.883, *df* = 6, *p-value* = 0.558, Fig. 3). Showing that roadkill by class occur randomly by highway shape.

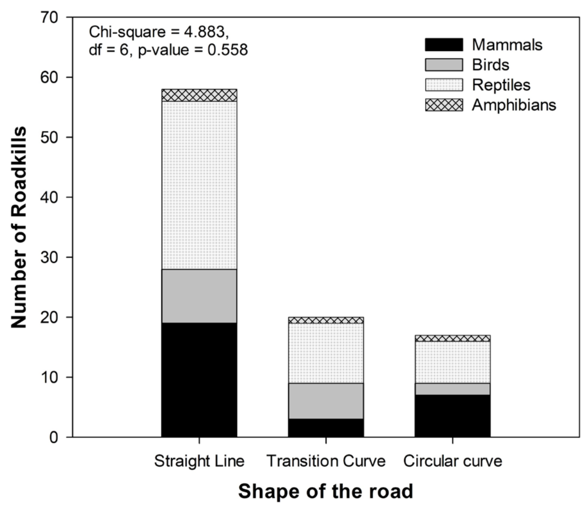

Figure 3: Distribution of the number of roadkills by animal class on the shapes of the road on the highway from San Jerónimo to the bridge of Santa Fe de Antioquia, in the Central Andes of Colombia.

The most frequent death was the Green Iguana *Iguana iguana* Linnaeus, 1758, representing 20% of the total roadkills, followed by the Common Opossum *Didelphis marsupialis*, Linnaeus, 1758 with 15.7% of total deaths (Table 2). Most of the roadkills occurred during the months of November and December 2018, and January, February and November 2019, doubling the number of deaths identified in most of the other months (Fig. 4).

Relating the total number of deaths detected in each unit of the highway shapes, we identified that 58 deaths occurred in only 27 of the 36 straight lines, the units occupying a length of 6,799.59 m; 20 deaths occurred in 15 of the 85 transition curves, the units occupying a length of 615.75 m; 17 deaths occurred in 11 of the 43 circular curves, the units occupying a length of 880.43 m. By dividing the number of deaths of each unit over the length of the shape units, we

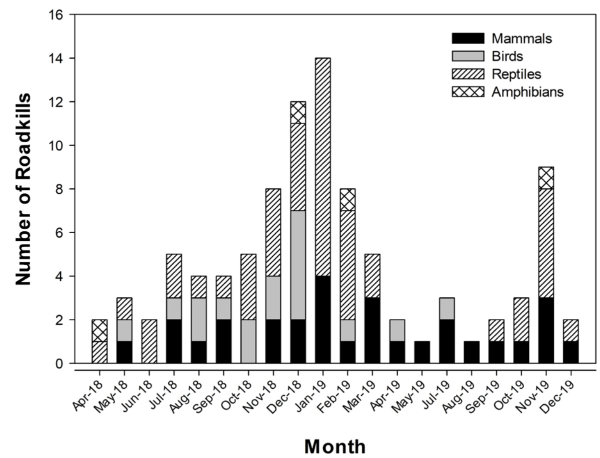

Figure 4: Distribution of the number of deaths by animal class over the sampling months, on the highway from San Jerónimo to the bridge of Santa Fe de Antioquia, in the Central Andes of Colombia.

found that the average proportion of mortality events per meter of the transition curves was three times greater than the mean of the straight lines; furthermore, the mean of the proportion of mortality events per meter of the circular curves was two times greater than the mean of the straight lines (Fig. 5).

The comparison of ranks in the proportion of mortality events per meter of the shapes of the road shows that there are statistical differences in the proportion of mortality events among shapes (*Kruskal-Wallis* = 28.351, df = 2, *p-value* < 0.001). Thus, when comparing which groups of shapes had statistical differences, it was found that the proportion of mortality events per meter of straight lines differed from transition curves (*Q* = -5.116, *p-value* < 0.001) and from circu-

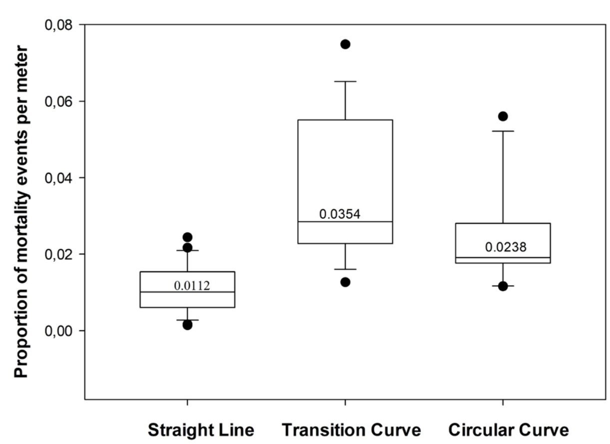

Figure 5: Comparisons of the proportion of mortality events per meter among the shapes of the highway from San Jerónimo to the bridge of Santa Fe de Antioquia, in the Central Andes of Colombia.

Table 2. Number of vertebrate roadkills per the shape of the road, on the highway from San Jerónimo to the bridge of Santa Fe de Antioquia, in the Central Andes of Colombia. SL = Straight line, TC = Transition curve, CC = Circular curve; Col = Colombia, Intern = International; LC = Least concern, VU = Vulnerable.

Taxa		**Number of roadkills per Shape of the Road**			**Threat level IUCN**	
AMPHIBIANS	**Species**	**CC**	**SL**	**TC**	**Col**	**Intern**
Order Anura	*Leptodactylus sp*	1			-	-
	Rhinella horribilis		2	1	LC	LC
REPTILES						
Order Serpentes	*Atractus sp*		2	1	-	-
	Boa imperator	2	9		LC	LC
	Clelia clelia	1			LC	LC
	Dendrophidion bivittatus	1			LC	LC
	Oxyrhopus petolarius		1		LC	LC
	Pliocercus euryzonus		1		LC	LC
	Pseudoboa neuwiedii		3	1	LC	LC
	Typhlops sp	1			-	-
Order Crocodylia	*Caiman crocodrilus*		2		LC	LC
Order Lacertilia	*Holcosus festivus*		1		LC	LC
	Iguana iguana	2	9	8	LC	LC
BIRDS						
Order Passeriformes	*Campylorhynchus griseus*			2	LC	LC
	Euphonia sp			2	-	-
	Sicalis flaveola	1	1		LC	LC
	Thraupis episcopus		1		LC	LC
	Forpus conspicillatus		1		LC	LC
Order Strigiformes	*Megascops choliba*		1		LC	LC
N/A	*N/A*			1	-	-
Order Accipitriformes	*Rupornis magnirostris*		3		LC	LC
Order Cathratiformes	*Coragyps atratus*	1	2		LC	LC
Order Cuculiformes	*Crotophaga ani*			1	LC	LC
MAMMALS						
Order Primates	*Aotus griseimembra cf*		1		VU	VU
Order Carnivora	*Cerdocyon thous*	1	4		LC	LC
	Nasua nasua		1		LC	LC
	Potos flavus		2		LC	LC
Order Pilosa	*Tamandua mexicana*	1	2		LC	LC
Order Didelphimorphia	*Didelphis marsupialis*	5	7	3	LC	LC
Order Chiroptera	*Molossus sp*		2		-	-
Number of roadkills per shape		**17**	**58**	**20**		

lar curves (Q = -2.905, p-value < 0.002); there were no statistical differences between the proportion of mortality events per meter of transition and circular curves (Q = 1.567, *p-value* = 0.058; Fig. 5).

The 2D hotspots identification analysis detected four road segments with considerable roadkill aggregation, in K0+550, K7+500, K8+500 and K10+500 sectors related to the curved segments of the highway (Fig. 6A, 6B).

The hotspot K0+550 was mostly surrounded by urban (40%) and forest covers (40%), with a stream less than 40 m away; K7+500 was mostly surrounded by urban cover (50%), and to a lesser extent forest cover (20%), with watercourses 281 m away; K8+500 was mostly surrounded by herbaceous cover (50%), and only 6% of forest cover, watercourses 259 m away; and K10+500 presented more than 80% of urban cover and 0% of forest cover, with watercourses 374 m away (Fig. 6B, Fig. 7).

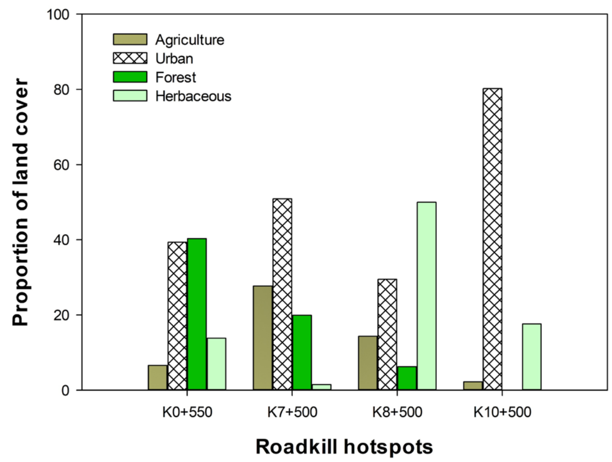

Figure 7: Proportion of land cover surrounding roadkill hotspots (300 m) on the highway from San Jerónimo to the bridge of Santa Fe de Antioquia, in the Central Andes of Colombia.

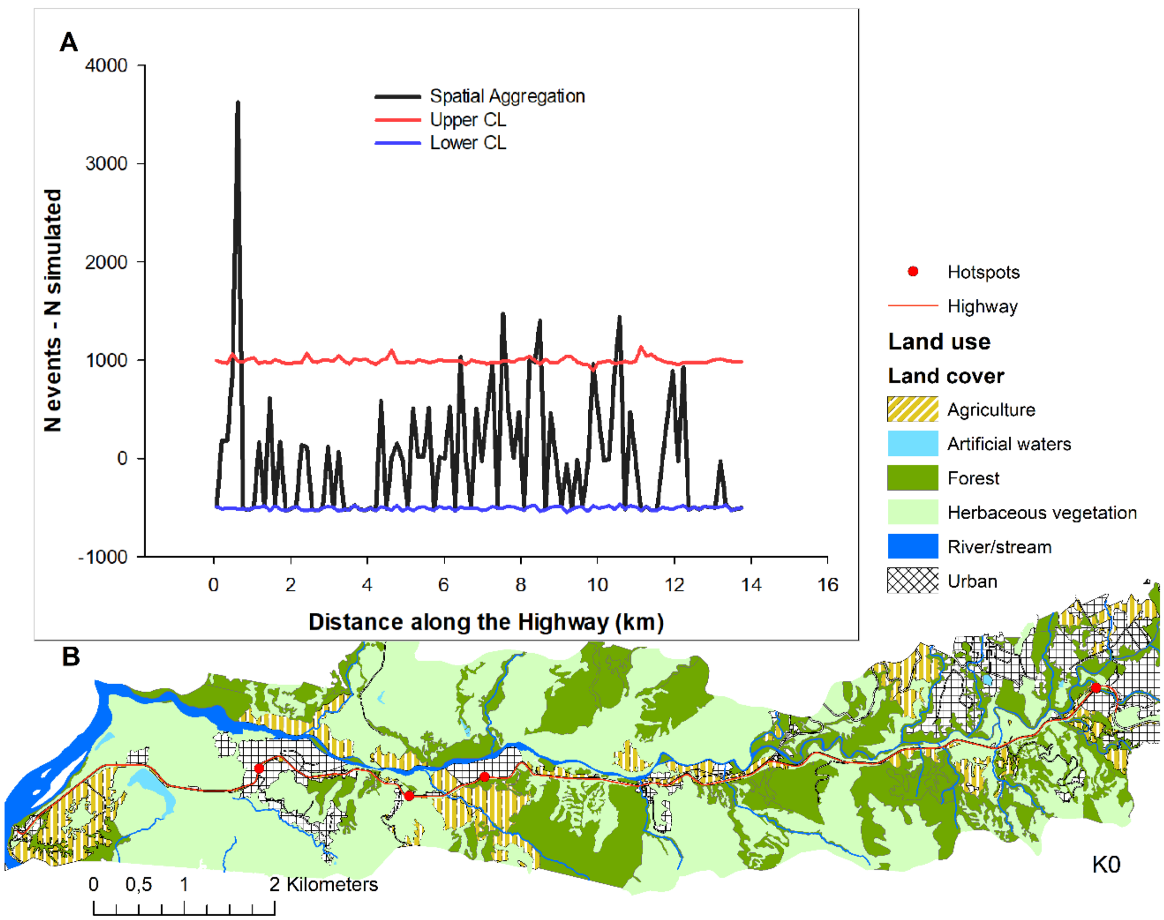

Figure 6: A, Roadkill hotspots along the highway from San Jerónimo to the bridge of Santa Fe de Antioquia, in the Central Andes of Colombia. The blue and red lines represent the lower and upper 95% confidence limit (Lower CL, Upper CL), and the black line represents the spatial aggregation of the roadkill data from which were subtracted the data points simulated by the Siriema software (N events – N simulated; Coelho et al., 2014). Values that exceeded the upper CL indicate the hotspots. **B**, Location of the four roadkill hotspots (red dots) at curved segments on the highway.

Discussion

Roadkills of arboreal species, such as *Aotus griseimembra cf.* and *Potos flavus* (Fig. 8g), show how this highway impacts forest-dependent species which are highly sensitive to habitat loss (McAlpine et al., 2002, 2006; Michalski & Peres 2007), and even more so *A. griseimembra cf.* a vulnerable nocturnal monkey which is threatened by hunting, illegal trade, logging and livestock farming (IUCN 2020, https://www.iucnredlist.org), and from the obtained results, by road infrastructure; a species that should be taken into account when implementing strategies such as wildlife crossings.

We found a lower vertebrate diversity (30 spp) in our surveys than that reported in the nearby area of Antioquia (Cuartas-Calle & Marin 2014; Peña & Quirama 2014; Suárez & Basto 2014). The low number of species detected on the road may be explained by (1) the area surrounding the highway has the attributes of a dry forest, this is one of the most threatened ecosystems in the Neotropics (Avendaño et al., 2018), with a constant reduction of resources and transformation of forest to pastures, this practice leads to the decreasing presence of species (Stern et al., 2002), which can be reflected in the roadkill (Cáceres et al., 2010; Coelho et al., 2012); (2) Many vertebrate species avoid crossing roads and are restricted to the most conserved areas of the forests (Jaeger et al., 2005; McGregor et al., 2008).

The highest number of deaths occurred in November, December, January and February, these months correspond to the holiday periods in Colombia, which triggers both greater numbers of vehicles on the road, and a higher probability of accidents (Oxley et al., 1974; Arévalo et al., 2017). Also, the most roadkills were from the species *Iguana iguana* and *Didelphis marsupialis*, two animals commonly found dead on Colombian roads (Rodda 1990; Delgado-Vélez 2014; Castillo-R et al., 2015; De La Ossa & Galván-Guevara 2015); where *I. iguana*, has the

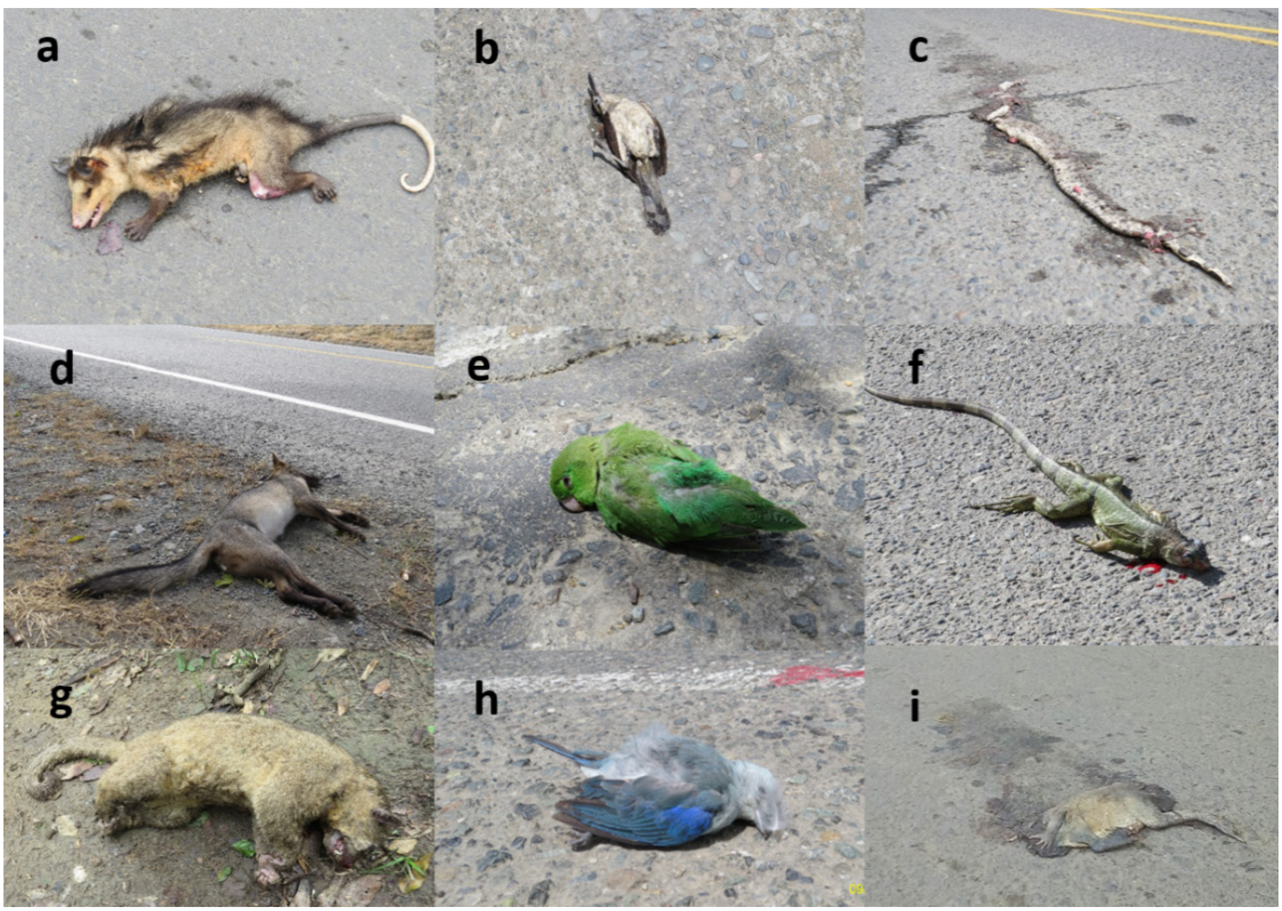

Figure 8. Some individuals of different species found death on the Highway from San Jerónimo to the bridge of Santa Fe de Antioquia, in the Central Andes of Colombia. a) *Didelphis marsupialis*, b) *Campylorhynchus griseus*, c) *Boa imperator*, d) *Cerdocyon thous*, e) *Forpus conspicillatus*, f) *Iguana iguana*, g) *Potos flavus*, h) *Thraupis episcopus*, i) *Rhinella horribilis*.

habit of basking on the edges of the roads (Townsend et al., 2003), like many other reptiles (Colino-Rabanal & Lizana 2012); and *D. marsupialis* with its nocturnal behaviour of eating carrion on the roads, when the lights of the vehicles shine in the opossum's eyes, they remain still, making them more susceptible to be roadkilled (Delgado 2007; Castillo-R et al., 2015). These behaviours and the fact that both are species with high population density (Rodda 1990; Pinowski 2005; Castillo-R et al., 2015) may explain their high number of deaths in our study.

In contrast, amphibians evidenced the lowest number of deaths (four roadkills), which can be explained by amphibians presenting a lower diversity of species in dry forests (Duellman 1988), also as they are dependent on aquatic ecosystems, some species avoid dispersion by open areas such as asphalt, because the absence of arboreal substrates and leaf litter create the risk of desiccation (Vargas-Salinas et al., 2011). Furthermore, given their small body size, amphibians tend to be obliterated under car wheels, scavengers can remove them quickly leaving no remains, and as a consequence, their deaths may be unobserved during surveying (Slater 2002; Mazerolle 2004).

Although the straight lines represented more than 58% of the horizontal alignment of the highway, the proportion of mortality events per meter of road shapes showed that transition and circular curves presented more animal deaths when controlling by size. Straight lines are designed to promote a continuous speed because the viewing distance between subjects and horizon is not affected as it is in curves (Invías 2008), allowing to detect an obstacle within a certain stopping distance. In Colombia, the legal speed limit for driving on highways in a straight line is 80 km per hour, reducing to 70 km/h or 60 km/h when reaching a curve. At 80 km/h, an obstacle has to be seen about 130 m ahead (Invías 2008), so if an animal crosses the road suddenly, at a distance less than is required for a vehicle to stop, the risk of an accident increases (Easa 2000; Invías 2008; Zilioniene & Vorobjovas 2011). However, the mean distance of units of straight lines was 227 m (Table 1), giving at least a higher possibility for a vehicle to stop or to avoid an animal.

The most dangerous road shapes for animals when crossing roads seem to be the curved segments, horizontal and probably vertical (although this could not be tested). This is due to the vehicle stopping distance needed when identifying an obstacle (or to see a vehicle approaching from the animal's perspective). For the highway in our study, according to the design, the continuous speed approaching from a straight line passing to a curve in a horizontal alignment is 70 or ≤ 60 km/h, depending on the variation of the radius of the circular curve and the speed of the previous segment (Comte & Jamson 2000; Invías 2008). Where the radius has larger dimensions, the manoeuvrability of the vehicles is facilitated, reducing their deceleration, thus implying less reduction in speed when entering curves (Retting & Farmer 1988; Comte & Jamson 2000; Charlton 2004; Invías 2008); also at 60–70 km/h, a vehicle needs from 85 to 105 m of stopping distance if an obstacle is on the road (Invías 2008). The mean length of units of transition curves was 37 m, and circular curves were 58 m, both being too short a distance of visibility for a vehicle to stop if an animal suddenly moves onto the road. Transitional curves particularly are the most dangerous segments, since they are positioned at the beginning of a circular curve, being areas with reduced visibility (blind points), giving less opportunity for drivers to swerve and for animals to escape (Lee et al., 2004; Charlton 2007).

There is no association for the distribution of deaths by class of animals with the shape of the road, which indicates that the roadkills did not occur due to the preference of certain animals to cross at a particular road shape, that is, at straight lines or curves; animals are more likely to cross to sites with higher vegetation cover, where a greater concentration of resources is possibly found (Coelho et al., 2008). The greatest aggregation of roadkills occurred at the Hotspot K0+550, which is similarly associated to patches of riparian forest and urban cover, as well as to a watercourse less than 40 meters away. However, similar to the others hotspots, which were associated to highly degraded areas such as agriculture and urban cover, and were far from watercourses (> 200 m), K0+550 was on a curved segment of the highway. As found in the literature, the highest roadkill aggregations tend to be associated with animal crossing patterns in forests patches and close to watercourses, sites with greater resources for wildlife (Coelho et al., 2008, Bueno et al., 2013; de Freitas et al., 2015; Magioli et al., 2019), however, as found in this study, it is shown that the geometrical design of roads can also influence the spatial aggregation of wildlife roadkills.

This research is presented as a starting point for conservationists, ecologists and road engineers to combine efforts for reducing wildlife roadkills and therefore accidents, with strategies such as: well-marked curves, i.e., vertical signs and surface marking treatments that inform the driver of the need to decelerate before a curve (Retting & Farmer 1988; Comte & Jamson 2000; Charlton 2004, 2007; Invías 2008); and the construction of curves with a larger radius, providing more space to manoeuvre a vehicle (Comte & Jamson 2000; Invías 2008). These aspects related to geometric road design, along with multi-species wildlife crossings, road barriers (for animals) and education and training for drivers should influence management and conservation plans focused on responding to biodiversity loss in altered ecosystems with the presence of road infrastructure.

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