Preventing wildlife roadkill can offset mitigation investments in short-medium term

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Abstract

Wildlife vehicle collisions (WVC) are a threat to wildlife and humans, killing millions of animals of numerous species, as well as causing significant damage to vehicles, drivers and passengers. Road fencing is a highly effective mitigation measure at reducing WVC, however its large-scale implementation requires a high investment. We questioned how long it would take for savings from avoided collisions to offset the investments in road fencing mitigation, focusing on vehicle damage costs. Using the information of a 3-year systematic roadkill monitoring of 1,158 km in Mato Grosso do Sul, Brazil, we estimated the real number of casualties accounting for bias in roadkill counting. We obtained information on the material costs on cars and trucks due to WVC and, considering the road traffic volume characteristics, estimated the total material costs resulting from collisions with larger animals. Cost-benefit analyzes allowed estimating the time required to amortize the investment in fencing, considering its application along the full surveyed roads or only in hotspots of mortality. We recorded over 10,000 WVC, 40% of which involved animals that can cause significant material damage to vehicles, namely the endangered lowland tapir (*Tapirus terrestris*, n=267) and giant anteater (*Myrmecophaga tridactyla*, n=608). The average material cost per accident was US$ 885±1,575 (mean±SD). We show that investments are likely to pay off in 16-40 years for the mitigation of the full roads, and in 9-25 years for hotspots of mortality. Thus, road mitigation is a win-win solution for increasing traffic safety for humans and reduce road-related negative effects on biodiversity.

Keywords: Road fencing, road-mortality, endangered species, material damages, carcass persistence, cost-benefit analysis.

1 Introduction

Roads are the most common human-made features on the globe, spreading across nearly all of its surface (Ibisch et al. 2016). An additional 25 million km of new roads are expected to be built by 2050, 90% of which in developing countries (Dulac 2013), particularly in tropical regions, which have support exceptional biodiversity and vital ecosystem services (Laurance et al. 2001, 2015, Alamgir et al. 2017). These infrastructures allow human population development by facilitating the movement of people and goods, as well their accessibility to different services, e.g. schools and markets (Ali et al. 2015). However, particularly outside urban areas, roads can also become areas of conflict with biodiversity, notably due to the high number of wildlife-vehicle collisions (WVC). For example, over two million mammals are estimated to be road-killed every year solely in Brazil (González-Suárez et al. 2018).

Collisions with wild animals, mainly large ones, can also be a serious threat to human safety, causing significant injuries to drivers and passengers, in addition to considerable economic impact (Bissonette et al. 2008, Huijser et al. 2009, 2013, Abra et al. 2019). In USA, it is estimated that 1-2 million WVC occur involving large mammals, of which ca. 5% cause human injury with costs surpassing US$ 8bn (Huijser et al. 2008). In California, in particular, it was estimated a material damage cost of US$ 76 million due to large wildlife-vehicle collision, for 2018 alone (Shilling et al. 2019). The annual cost of WVC involving ungulates in Sweden was estimated at US$ 406 million (Gren and Jägerbrand 2019), and in the São Paulo State, Brazil, the total annual cost to society was estimated at US$ 25 million (Abra et al. 2019). Yet, there is a great lack of knowledge about the material costs that WVC entail in most regions, even though this information is particularly relevant for making decisions about the implementation of mitigation measures on roads.

Roadkill data is usually acquired through systematic monitoring of roads. However, roadkill surveys generally fail to fully record all casualties due to imperfect detection issues, and yet accurate estimation of the total mortality is important for precise estimates of the material costs associated with WVC. Imperfect detection may be due to one or more detection biases, including: *i*) researchers failing to find carcasses along the road or verges while surveying the road; *ii*) traffic volume, scavengers or management staff removing carcasses before searches are conducted; and *iii*) carcasses ending up outside the searched area (Santos et al. 2011, 2016, Teixeira et al. 2013). To account for such biases, researchers typically conduct field trials to estimate the effects of the first two components (Barrientos et al. 2018). For the third component, while generally less considered in mortality estimates, one can perform extra surveys outside the road corridor to count the number of carcasses therein or search for signs of injured animals.

Once a detailed knowledge of roadkill patterns is obtained, different mitigation measures can be considered to reduce WVC. Fencing is one of most common mitigation measures, and one with higher effectiveness at reducing road mortality, particularly when connecting to existing road passages (Seiler et al. 2016, Rytwinski et al. 2016, Spanowicz et al. 2020). Other measures, such as raising the road on pillars or placing the road underground are potentially more effective than fencing but are also cost prohibitive and unrealistic for most regions. Conversely, less expensive measures than fencing, such as wildlife warning signs and reflectors, are apparently ineffective (Rytwinski et al. 2016, Brieger et al. 2017, Benten et al. 2018). Hence, while also requiring regular maintenance, wildlife fencing seems to be an important cost-effective strategy for road mortality mitigation of most species (Seiler et al. 2016, Rytwinski et al. 2016, Spanowicz et al. 2020).

Due to financial constraints, it is rarely realistic to fence an entire road network simultaneously, and thus mitigating particular road sections may be more cost-effective than fencing all roads (Ascensão et al. 2013, Spanowicz et al. 2020). One common approach is to focus on road sections with significant aggregation of collisions (Spanowicz et al. 2020).

Given that collisions with large body mass species represent a higher threat for humans, with corresponding higher material costs, fencing may be more beneficial in sections where these species tend to be more road-killed, as where roads cross landscape connectivity corridors (Grilo et al. 2011, Santos et al. 2017), in opposition to fencing where higher overall roadkill occurs.

Knowledge of the patterns of mortality, namely how it varies along time, its spatial aggregation, and their costs allow for better management of existing roads as well as better planning for future road networks. This information is even more necessary in developing regions where road networks are expected to have greater expansion and impact in near future (Meijer et al. 2018, Ascensão et al. 2018, Ascensão 2020). In this study, our main goal was to estimate the material costs due to WVC in a region of fast development as is the state of Mato Grosso do Sul, Brazil. The reduction of roadkill is essential therein due to the large number of WVC that has been evidenced in several studies, but also due to the threat to human safety that collisions with species of large body mass represent, including the lowland tapir (*Tapirus terrestris*), giant anteater (*Myrmecophaga trydactyla*) or capybara (*Hydrochoerus hydrochaeris*) (Ascensão et al. 2017, 2019).

We used the information from a 3-year systematic roadkill monitoring program over of 1,158 km, for which we estimated the real number of casualties accounting for bias in roadkill counting. We obtained information on the material costs on vehicles (cars and trucks) due to WVC from car mechanics and online surveys and estimated the total material costs resulting from collisions with larger animals considering the traffic volume characteristics (proportion of cars and trucks). We then performed a cost-benefit analysis comparing the costs of material damage with the necessary investment to implement fences (e.g. Huijser et al. 2009), either along the full road corridor or only in sections with significant roadkill aggregation (i.e. hotspots of mortality). With this information we estimated how long it would take to obtain a return on the investment in fencing that prevent collisions, considering the avoided costs due to WVCs.

2 Methods

2.1 Study area

The study was conducted in the state of Mato Grosso do Sul (MS), located in center-west region of Brazil, throughout six different transects on four roads (Fig.1), namely the federal roads BR-262 (R1A, R1B and R4) and BR-267 (R3B), and the state roads MS-040 (R2) and MS-338 (R3A), totaling 1,158 km (Fig. 1, Table 1). All roads have two-lanes and are paved.

[FIG. 1]

The land use bordering these roads was dominated by grassland/pasture and agriculture, followed by remnant native vegetation and riparian areas. The westernmost transect (R4) runs through part of the Pantanal biome (Brazilian wetland, see Fig. 1) and has higher cover of native vegetation in its surroundings when compared to the other transects that cross the Cerrado biome (Brazilian savannah). Urban areas had relatively low representation in the study area and were not surveyed in road transects. Traffic volume was similar across transects in the two federal roads (BR) surveyed, ca. 3,600 vehicles per day, of which 33-48% were trucks (DNIT 2020; Table 1). In roads R2 and R3A, there were no official traffic counts, so we recreated the methodology used by governmental authorities (DNIT 2020), namely vehicle counting throughout a full week (24 h per day) (Table 1). The climate throughout MS is wet from October to March and dry from April to September (Koppen’s As or Aw), with mild year-round temperatures (range 21-32°C). Average annual rainfall ranges between 1000-1500 mm.

[TABLE 1]

2.2 Roadkill systematic surveys

Roadkill surveys were carried out by car (40-60 km/h), searching for road-killed animals on both lanes and shoulders. The choice to carry out research by car and at this speed was due to the aim to cover a large territory and to record wildlife carcasses with body mass >1 kg. Monitoring lasted three years on a fortnightly basis (average interval of 14.5 days) (Table 1). The monitoring on R1B was interrupted after one year of survey for safety reasons, given the lack of safe places to park the car when an animal was detected. A total of 420 survey events were performed, totaling 84,673 km of survey effort. Each observation was classified to species level (when possible) and its location recorded with hand-held GPS before carcasses were removed from the road to avoid recounting or road accidents.

2.3 Carcass persistence time

In parallel with road surveys, we carried out experiments to assess the effect of carcass removal, in order to more accurately estimate the real number of WVC. Experiments were performed both in wet and dry seasons, on 337 km of three of the surveyed transects, one with low traffic volume (R2) and two with higher traffic volume (R3B and R4). These sections were surveyed on a daily basis for 15-30 days (mean 25.9 days) (Table 2). All animals found on the first day were discarded and in the following days all road-killed carcasses were left intact, where detected, recording the species identification (or lower taxonomic level), its approximate weight and their condition (detectable or not). In total, 423 carcasses with body mass >1kg were followed, 268 with less than 5 kg (hereafter <5 kg), 124 between 5-30 kg (hereafter <30 kg) and 31 with more than 30 kg (hereafter >30 kg); 207 in wet season and 216 in dry season (Table 2).

[TABLE 2]

2.4 Material costs of collisions

We obtained wildlife–vehicle collisions data from Mato Grosso do Sul State containing information about the accident, including the species involved, vehicle type (car, truck, other), and damage to the vehicle. Photos of the accident taken by the road company staff allowed to confirm the species involved in WVC. An estimate of the cost to repair each vehicle was then requested to three different vehicle repair shops in Campo Grande and then averaged. In complement, we created an online questionnaire with the Google forms platform (Supplementary material S1) and disseminated in social networks. There, we asked about the date, place and period of the day (day, night, sunset, sunrise) of the collision events; the type of vehicle (car, truck, other); name or description of the species involved in collisions; and the cost of the material damage, if any. A section for adding observations was also included in which citizens could provide details about the accident (e.g. whether the vehicle has been irreparably damaged).

2.5 Data analysis

2.5.1 Species potentially causing vehicle damage

All species detected in collisions (systematic surveys) were first characterized according to their likelihood of causing material damage to vehicles when involved in collisions. Based on information from material damage (interviews and questionnaires, see Results), we classified as potentially causing damage those species with body mass >1kg, excluding all reptiles such as caimans, and short stature mammals as armadillos. Flying birds were also not considered as fencing (the mitigation method considered here) is unlikely to reduce collisions with these species. Overall, we considered mammals with >1kg and the non-flying bird greater rhea (*Rhea americana*). Those species likely to cause material damage were further classified in three body mass classes (kg): <5, <30 and >30 (see Table S2.1 in Supplementary material S2 for full classification).

2.5.2 Estimating total number of roadkill

We estimated the real number of roadkills that occurred during the survey period, for each road transect, using the GenEst framework and corresponding R package (Simonis et al. 2018, Dalthorp et al. 2020). This software integrates data collected during carcass searches together with estimates of carcass persistence, search area and searcher efficiency, to accurately estimate the real number of collisions and to provide a measure of precision associated with the estimate. GenEst was designed to address the general problem of estimating the size of a population when not all animals are present on all survey occasions and the probability of detection is less than one (Simonis et al. 2018). Following Dalthorp (2018), GenEst is an elaboration of a binomial probability model X ~ binomial (M, g), where X is the observed number of carcasses and g is the detection probability. If g is known, then $M' = X/g$ is an unbiased estimator for M and the sampling variance of X is the only source of uncertainty about M. Splitting the total mortality into groups, e.g. A and B, then $M' = M'_A + M'_B = X_A / g_A + X_B / g_B$ is unbiased for M (Dalthorp et al. 2018). GenEst makes extensive use of this simple idea of splitting the carcass observation data into distinct subgroups, estimating mortality in each subgroup, and combining subgroups into larger groups by summing. Further details are extensively documented in GenEst supporting documents (Dalthorp et al. 2018, Simonis et al. 2018). We used GenEst to model carcass persistence time and, together with estimates on searcher efficiency and the area searched along the road, to estimate the total mortality for the different body mass groups per road transect.

Carcass persistence was modelled using the data from our experiments, to estimate the amount of time a carcass would persist for, given the conditions under which it arrived. For each body mass class, four classes of parametric models of carcass persistence were tested: exponential, Weibull, logistic, and lognormal. In each model we further tested the effect of traffic volume (high/low) and season (wet/dry) on the persistence probability, by comparing models including all combinations of these two predictors together with the null model, according to the Akaike Information Criterion (AIC). Models were selected based on AIC values, considering that $\Delta AIC<2$ indicate similar models (Burnham and Anderson 2004).

As for searcher efficiency (SE), estimating this component requires a different set of experiments, where the carcasses are disposed by other people in known locations, and roadkill surveyors have to detect them. The detection error rate provides an estimate of the detectability (Santos et al. 2016). Due to logistic constrains we did not carry out these experiments. However, researchers were highly experienced in roadkill surveys in our study area (Ascensão et al. 2017), and based on this experience we estimated that we could detect at least 85% of carcasses with >1kg on the road. Given the uncertainty of the real value, we used different values of SE for estimating total mortality: 0.85, 0.90, and 0.95. For carcasses with lower body masses, we expected a much lower detection probability (Boves and Belthoff 2012, Teixeira et al. 2013, Santos et al. 2016, Barrientos et al. 2018) and therefore were not considered in mortality estimations.

Regarding the search area (SA) along the road corridor, it is known that many carcasses are projected off the road during the collision, and that injured animals may still be able to move away from road lanes and shoulders. It follows that a proportion of the carcasses can never be detected. From our experience in the study area, whose investigation includes occasional surveys on the verges, we know that some larger animals die away from the road, while smaller species are projected far from the road lanes. Again, to tackle the uncertainty on this parameter, we also used different values of SA for estimating total mortality: 0.80, 0.85, 0.90, and 0.95, i.e. between 5-20% of all carcasses never fall into a detectable area, the road pavement and verges.

Using GenEst, we estimated the total mortality for the six different transects, per body mass classes, and using the different combinations of SE and SA (12 models) considering *i*) the dataset of records >1kg and *ii*) only those species likely to cause material damage to vehicles. For each model, the accuracy of estimates was measured through 2000 replicates.

2.5.3 Determining spatial aggregations of collisions

The records pertaining to species likely to cause material damage were aggregated by body mass class (<5, <30 and >30 kg) and by road sections of five km length. This segment length was chosen to minimize the chance of spatial variation of hotspot location with time (Santos et al. 2017), while also being a reasonable distance to apply mitigation measures such as fencing (Seiler et al. 2016). For each transect and body mass class, we assumed that the observed number of roadkill per road section would follow a random Poisson distribution with a mean (λ) equal to the total number of roadkill divided by the total number of road sections (Malo et al. 2004, Santos et al. 2017). The probability of any road segment having *x* number of collisions was therefore:

$$p(x) = {}^{\lambda^x}\!/_{x!\,e^{\lambda}}$$

A mean value (λ) for each body mass class and road transect was calculated. We considered a road section to be an aggregation of collisions, i.e. hotspot of mortality, when $p(x) > 0.95$. We preferred using this conservative value of p to reduce the likelihood of highlighting spurious aggregations, resulting from multiple comparisons (Borda-de-Água et al. 2019). We further assumed that the carcass persistence, searcher efficiency and search area were equal within and outside the road sections classified as hotspots, and therefore the proportion of animals not recorded in roadkill surveys was constant across each road transect. For example, if a transect had 100 records and a total mortality estimated in 120 records (i.e. 20% increase), a given road section of that transect having a significant aggregation of records, e.g. n=40, was assumed to have had a total mortality of 48 records (increase in 20%).

2.5.4 Cost-benefit analyses of road fencing

To estimate the material cost of collisions, we used the estimated total collisions with species potentially causing vehicle damage (see 2.5.1). For each body mass class, we calculated the mean of reported cost in interviews and online questionnaire, per vehicle type (car or truck). We assumed that the probability of an animal being hit by a car or truck was proportional to the traffic volume of each type of vehicle. Hence, the cost calculation considered the mean traffic volume in each road transect, per vehicle type. For example, the estimated cost of WVC in the R4 transect (with 33% of traffic of trucks and 66% of cars) was calculated as follows:

$$0.33 * \text{cost with trucks } (N_{<5} + N_{<30} + N_{>30}) + 0.66 * \text{cost with cars } (N_{<5} + N_{<30} + N_{>30}),$$

where N are the number of individuals from total mortality estimates, of each body mass class.

The material costs were estimated separately for each full transect (considering all WVC along the road) and for the sections were aggregations of collisions were detected (WVC in hotspots). We then performed simple cost-benefit analyses for each road transect, by estimating the return period in years, i.e. the time needed to pay off the investment made in mitigation measures (fencing) if it avoided 100% of collisions with those larger species. We also assumed a similar roadkill rate along time (i.e. without significant changes in the number of collisions along time). The return period was calculated as the ratio between the initial investment per km and the estimated cost per km and per year. We used as investment value US$ 34,056 per km of fencing (on both roadsides), obtained from the average budgets of three companies that apply fences on MS roads (see Supplementary material S3).

3 Results

3.1 Roadkill systematic surveys

We recorded 10,942 carcasses of road-killed animals of which 9,431 had a body mass >1 kg, including 4,208 larger animals likely to cause material damage with monetary cost to vehicles (see Table S2.1). The roadkill rate was generally higher in the transect R4 for species pertaining to body mass classes <5 and >30; and had similar values across transects for the intermediate class <30 (Fig. 2). A considerable proportion of animals pertaining to weight classes <30 and >30, mainly reptile species such as snakes and caimans, as well short stature mammals such as six-banded armadillo (*Euphractus sexcinctus*) and nine-banded armadillo (*Dasypus novemcinctus*), were also found in transect R4 (Fig. 2). The number of WVC seems to be increasing with time in some transects, namely R2, R3A and R3B (Fig. 2).

[FIG. 2]

3.2 Total mortality estimates

Carcass persistence models for the three body mass classes had a higher fit using Weibull distribution (Fig. S4.1 in Supplementary material S4). Overall, carcasses with >1kg were detectable for 4.3 ± 3.7 days, being the probability of a carcass persisting 15 days < 60%, with higher values for large body mass species (Fig. S4.1). Models of carcass persistence including the effects of season and traffic were similar (AIC < 1) to those not including these variables, and therefore we choose the simpler models (without those variables) to estimate total mortality. Using the carcass persistence models and the different combinations of search efficiency and search area, we estimated that total mortality of animals >1kg ranged between (median and 90% CI) 11,983 (11,424 – 12,661) and 15,108 (14,192 – 16,214), of which between 5,581 (5,245 – 5,965) and 7,072 (6,533–7,705) were with animals likely to cause material damage with monetary cost to vehicles (Fig. 3). Overall, there was an underestimation of mortality in roadkill surveys of ca. 22-38%. Hereafter, we will use two scenarios combining the extreme values of search efficiency (SE) and search area (SA), i.e. the one having higher mortality estimates (SE: 0.85, SA: 0.80) and the lower mortality estimates (SE: 0.95, SA: 0.95).

[FIG. 3]

3.3 Spatial aggregations of collisions

We identified 43 road sections (ca. 19% of total road length) having a significantly higher aggregation of collisions. We recorded in these hotspots 1,481 collisions with animals likely to cause material damage with monetary cost to vehicles, i.e. ca. 34% of the mortality with these species. The majority of these hotspots (n=18; 90 km) were in the transect R4 (Fig. 4). Using the two scenarios of SE and SA combinations, we estimated that a total of 1,376 – 1,744 (median values of each scenario) collisions were likely to have occurred in the hotspot sections, which we used in vehicle costs estimates. Noteworthy, hotspots covered a lower proportion of other smaller but highly road-killed species, including yacare caiman (*Caiman yacare*; 9% of its mortality), black-and-white tegu (*Salvator merianae*; 18%), or six-banded armadillo (29%) (see Table S2.1).

[FIG. 4]

3.4 Material costs in vehicles

We obtained information on material costs for 185 animal-vehicle collisions, of which 94% referred to animals with body mass >1kg. None of these involved collisions with reptiles or with short stature mammals, supporting our choice to focus on the greater rhea and larger mammals as potentially causing material damages (Table S2.1). The average material cost with animals >1 kg was US$ 885±1,575 (mean±SD). The mean cost per vehicle type (car and truck) and body mass ranged between US$ 65-2,133. Nine responses (5%) referred the total loss of the vehicle, with costs averaging US$ 6,505±1,626 (Fig. 5). The cost of hitting a >30 kg animal was considerably higher for trucks.

[FIG. 5]

The total costs resulting from the estimated mortality throughout the study period was estimated to range between US$ 4,455,730 and 5,645,009, with a cost value per road kilometer and per year averaging between US$ 1,171 and US$ 1,492 across the road transects, respectively for the lower and higher mortality scenarios. The hotspots of WVC represented 19% of the roads but aggregated ca. 36% of the potential costs with vehicle damage, i.e. US$ 1,593,485 – 2,018,779.

3.5 Cost-benefit analyses of road fencing

Considering an initial investment of US$ 39,436,848 to fence the whole surveyed transects (1,158 km; US$ 34,056 per km of fencing), we calculated the return period of investment considering the estimated mortality from lower and higher mortality scenarios. Accordingly, the return period would range between 16 and 40 years across the transects, if fencing the full length of transects (Table 4). On the other hand, the investment required to mitigate the hotspot sections would be significantly lower, US$ 7,322,040, and would have a return period ranging between 9 and 25 years. Transects with higher number of WVC with larger animals would have a shorter return period, namely the transect R4 (Table 3).

[TABLE 3]

4 Discussion

We performed over three years of roadkill monitoring in which we recorded >10,000 WVC along the 1,158 km. About 40% of collisions involved large animals that cause significant material damage to vehicles, some of which represent a real threat to human lives. Moreover, some of these larger species are of conservation concern and had considerable roadkill rates, such as the lowland tapir (267 records) and giant anteater (608 records), probably threatening their population persistence in the long term in this region (Medici et al. 2012, Desbiez et al. 2020). Furthermore, according to our estimates, the total mortality of species weighting >1 kg was 22-38% higher than the one recorded and therefore these numbers are likely to be highly conservative. Additionally, the number of WVC seems to be increasing, at least on some surveyed roads, probably reflecting the increasing traffic volumes in Mato Grosso do Sul (DNIT 2020). Overall, such high roadkill rates may have serious negative effects on wildlife population viability (Ceia-Hasse et al. 2018, González-Suárez et al. 2018, Desbiez et al. 2020), as well on human safety (Shilling et al. 2019, Abra et al. 2019, Gren and Jägerbrand 2019), and therefore the implementation of mitigation measures at least in key areas of the highway is highly necessary.

Fencing has been acknowledged as one of the most effective measure to reduce WVC, particularly when combined with faunal passages (Jaeger and Fahrig 2004, Seiler et al. 2016, Rytwinski et al. 2016, Spanowicz et al. 2020). There is evidence that several medium and large mammals that inhabit the region use existing passages, including tapir, capybara and giant anteaters (Abra et al. 2020). Hence, channel these species into passages through fences would likely result in greater road mitigation effectiveness. However, the large-scale implementation of fencing can be hindered due to the high initial investment required. Yet, our study shows that when compared to the cost of material damage of vehicles, such investments are likely to pay off in the medium term. According to our data, the initial investment necessary to fence the whole surveyed transects would have a full return in an average of 27 years. This period is shorter than most concession contracts, ca. 20-30 years. Also, to put these investments in perspective, the World Bank estimates that new bituminous two-lane highway costs ca. one million dollar per km (World Bank 2006), therefore suggesting that fencing investment represents about 1% of the presumed construction cost.

If surrounding the entire road network simultaneously is unviable due to the high budget required, focusing on road sections concentrating higher number of WVC involving larger species - at least in a first phase - would provide a much higher cost-benefit relation. We identified 43 sections that concentrated ca. 34% of WVC with larger animals. Fencing these sections would require 19% of the initial investment with a full return in much shorter periods. This is particularly evident in transect R4 which add most hotspots with larger animals, and for which about 9-11 years would suffice to compensate the initial investment.

It should be noted that focusing on hotspots of mortality, while greatly reducing the investment required in mitigation, potentially fails to reduce significantly the mortality of other species. Particularly in transect R4, we recorded a high number of reptiles as caiman and short stature mammals as armadillos that would not be protected by exclusionary fencing, if it was applied only in hotspots. Likewise, fencing is not effective in reducing collisions for most birds. Yet, these species can be heavily impacted by roadkill (Loss et al. 2014, González-Suárez et al. 2018), and may also represent a danger for traffic. For example, although not considered in our estimates, our dataset contains records of accidents with smaller birds, such as the red-legged seriema (*Cariama cristata*), causing material damages averaging US$ 520 (n=7). Therefore, road fencing in the sections with the highest mortality should be considered an important step, but not an isolated one in the road mitigation process.

The average material cost per accident (US$ 885±1,575) was considerably lower than the one reported for other regions in Brazil such as in the São Paulo state US$ 5,000 (Abra et al. 2019), or in other studies from developed countries, namely US$ 7,000 in Spain (Sáenz-de-Santa-María and Tellería 2015) and US$ 11,900 (with large animals) in California (Shilling et al. 2019). Such disparity of values probably stems from differences in the cost of living across countries and regions of Brazil. Accordingly, the investment required to install fences that we have obtained is considerably lower than the one reported by Seiler (2016) for fences targeting ungulates in Europe, budgeted at US$ 44,000 – 65,000 per km road. Hence, for regions or countries with higher material costs, the return periods are probably similar to the ones estimated here.

The material damage in cars was in average higher when compared to trucks. This was expected given the higher shaft height of trucks, that allows them to run over animals without major damages. The exception was for trucks colliding with larger mammals (>30 kg), which had considerable higher costs, over US$ 2,000, relatively to cars. When a truck hits a lowland tapir, it collides against a 150-250 kg body mass animal, with a shoulder height of 77 to 108 cm (Padilla and Dowler 1994). That is, it hits a large and heavy object, potentially damaging different parts of the vehicle. Conversely, car passengers can be seriously injured or killed when colliding with these animals. For example, between April 2013 and March 2020, 77 people were injured and 28 died in collisions with tapirs on different roads of Mato Grosso do Sul (Patricia Medici *pers. comm.*). Moreover, in tropical countries, roads have mostly two lanes, often without wide shoulders, and therefore the entry of animals on the road may not be perceived by drivers, especially at night. Therefore, preventing animals from accessing roads by diverting them to under or over passages is imperative in regions where these large animals roam, both for their conservation and human safety.

It should be emphasized that our estimates only considered the material damages in vehicles and are therefore highly conservative figures. We did not include values on human lives and injuries, due to the difficulty in assigning them monetary value. Yet, when available, these values would significantly lower the return period of investments (Wijnen and Stipdonk 2016). For example, Sáenz-de-Santa-María and Tellería (2015) mentions compensations of US$ 1,655,750 for fatally injured people; US$ 259,000 seriously injured people; and US$ 7,210 for minor injuries; and in São Paulo state, the average cost for a crash with human injuries or fatalities is US$ 29,813 (Abra et al. 2019). In addition, there are other costs associated with WVC not counted here, namely those associated with traffic police and medical assistance, road repair, traffic congestion and resulting delays, removal of carcasses, searches for injured or dead animals and the value of animals lost. As an example, jaguar (*Panthera onca*) ecotourism in Pantanal represents a gross annual income of US$ 6,827,392 (Tortato et al. 2017), and therefore roadkill of these animals has a serious impact on both biodiversity and local economy. Also, collisions often imply delays in traffic, with consequent costs, which can be even more problematic in Brazil, a country where most transportation of goods often relies on trucks. On the other hand, to guarantee its effectiveness, fences must be carefully planned and properly installed. For example, for species capable of climbing it is required to use smaller mesh size or gravity walls, which are known to provide an effective and long-lasting barrier impeding smaller animals to access the road (Kenneth Dodd et al. 2004, Baxter-Gilbert et al. 2015) (see Supplementary material S3). Furthermore, fences require regular inspection, maintenance and repair, which will raise the associated costs.

Overall, accounting for all the different costs related with WVC, from material damage to insurance payments and general road maintenance, would provide a more precise evaluation of the economic savings of road fencing. However, using the costs associated only to material damages in this simple cost-benefit analyses already provided valuable information to help decision makers to evaluate the feasibility and need of implementing road mitigation structures. Both the number of injured people and roadkill rates may worsen in the future, with the increasing development of road networks and traffic volume worldwide (Meijer et al. 2018). This is particularly true in countries of great diversity where new development corridors are being planned, cutting into areas hitherto pristine (Laurance et al. 2015, Alamgir et al. 2017, Ascensão et al. 2018).

In conclusion, this study shows that investments in road mitigation using properly installed fencing and connected to safe crossing passages, are likely to be paid off in medium term. Investing in mitigation measures provides a win-win solution for increasing traffic safety for humans and reduce road-related negative effects on biodiversity.

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Figures

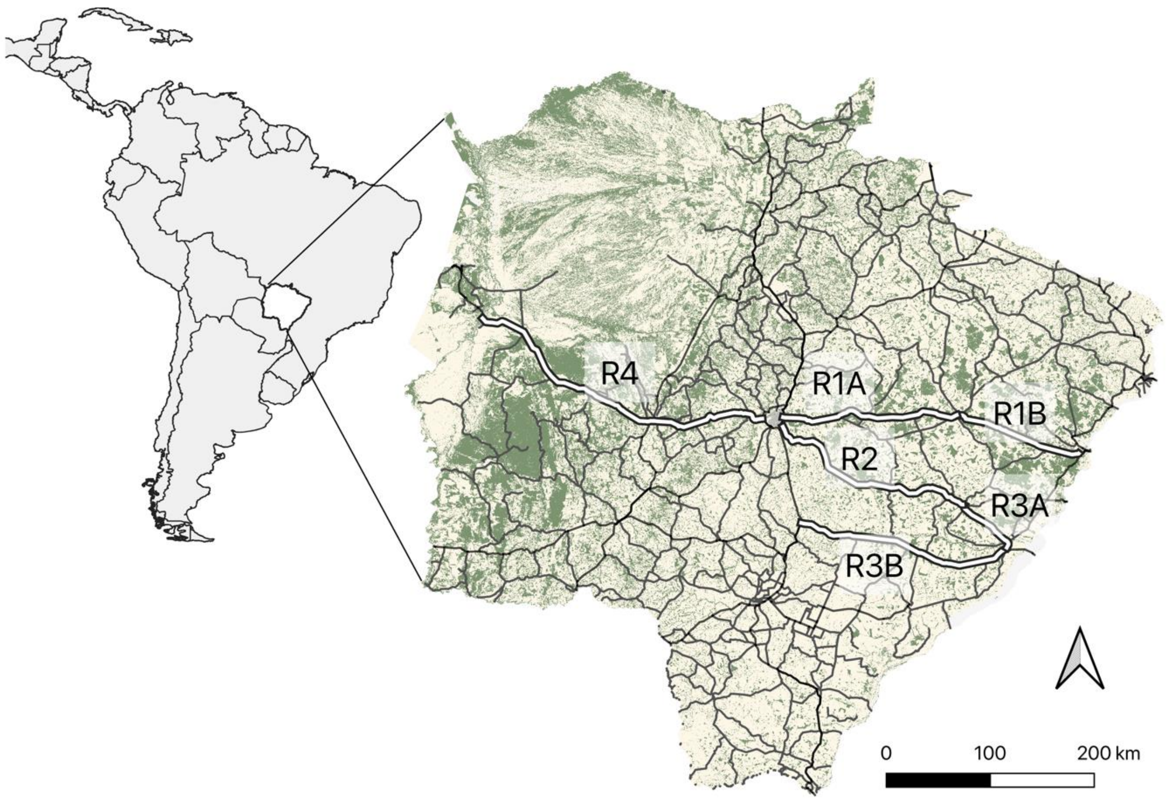


Figure 1 – Location of the surveyed roads in Mato Grosso do Sul, Brazil. Surveyed transects are shown in white. The study was conducted on federal roads - R1A, R1B and R4 in BR262, and R3B in BR267; and on state roads – R2 (MS040) and R3A (MS338); totaling 1,158 km. Main road network is depicted as black lines. Main land use classes are forest (darker areas) and open areas, including agriculture and pastures (lighter areas). Land use was reclassified from MapBiomas (Azevedo Sr et al. 2018). The city Campo Grande is in the middle of the State. The Pantanal is the upper left region of the map.

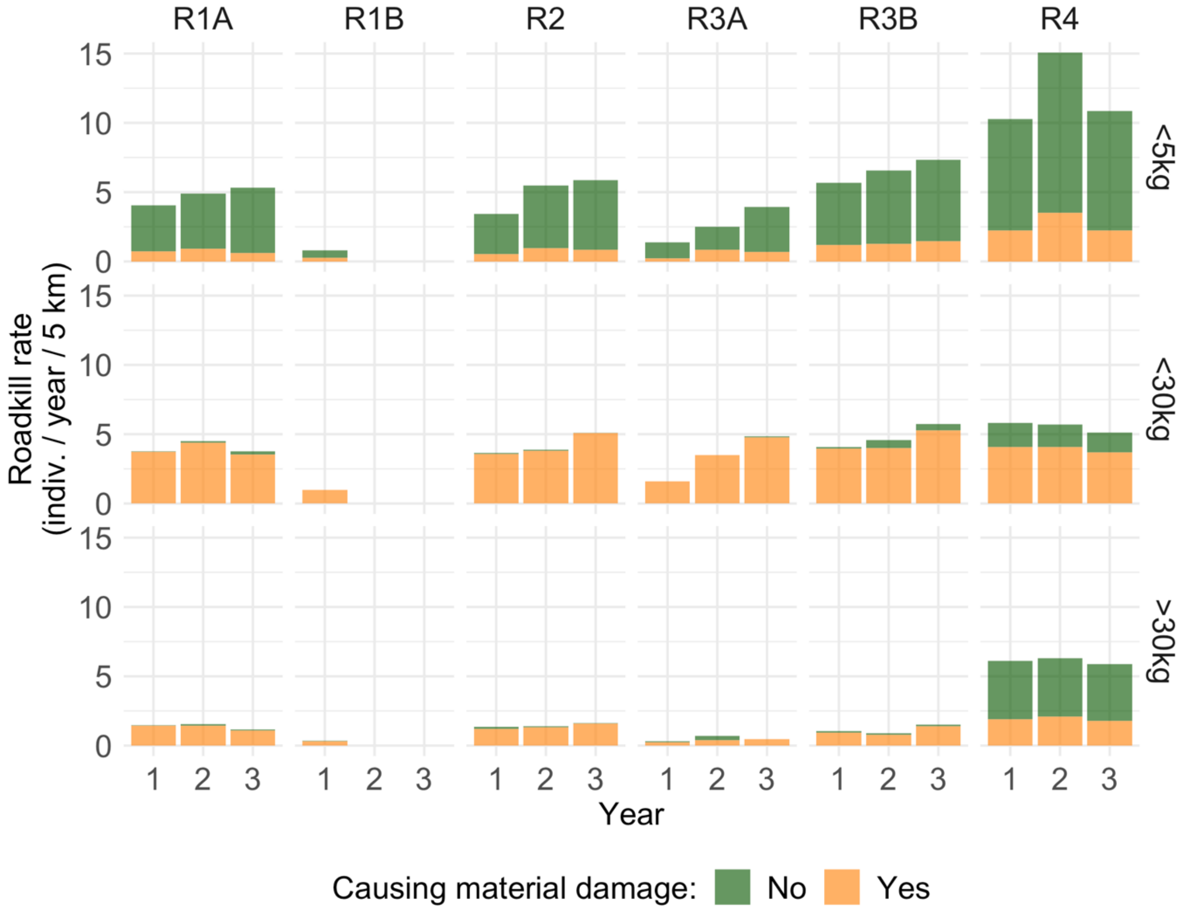


Figure 2 – Roadkill rate (individuals per year and per 5 km) recorded along the 3-year study period for the six road transects, per body mass class. Values are aggregated according to the likelihood of a species causing or not material damage in vehicles.

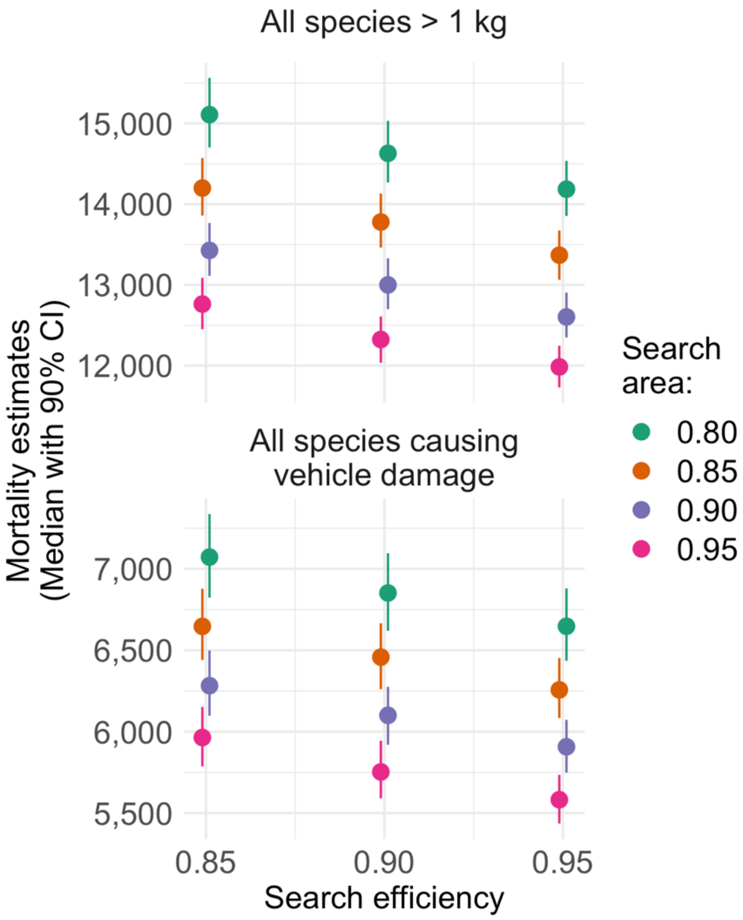


Figure 3 – Mortality estimates (median and 90% CI) for all species weighting >1 kg (top), and for the subset of species likely to cause damages in vehicles in collisions (bottom), according to different levels of Search efficiency (x-axis) and Search area (colors). Points are slightly scattered to allow a better reading, due to overlapping CI.

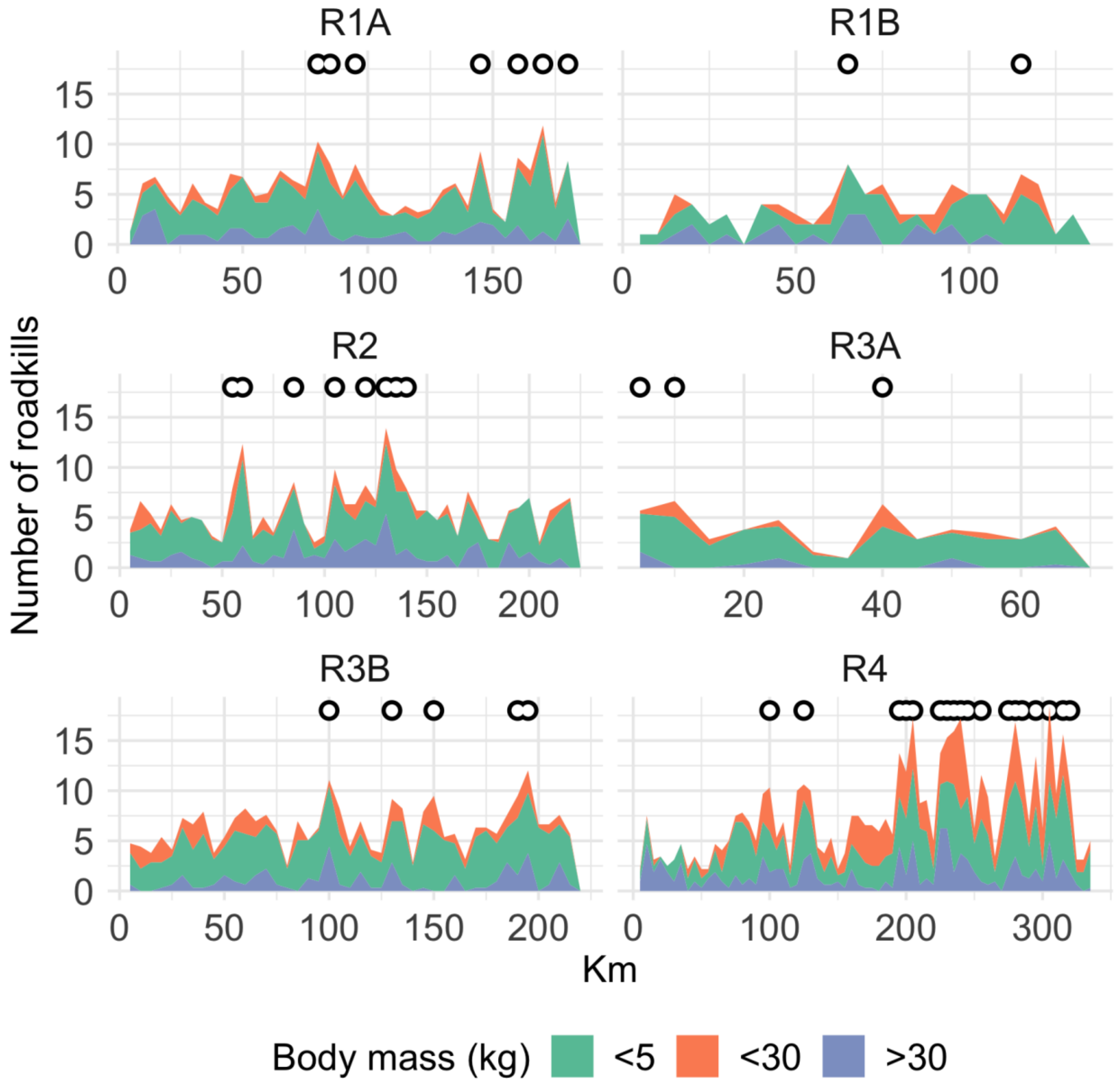


Figure 4 – Spatial patterns of roadkill (individuals per 5 km road section, per year), involving species likely to cause material damage with monetary cost to vehicles, per body mass class and road transect. Dots on top of each panel indicate hotspots of mortality with probabilities of 0.95. Transects are oriented west-east (see Fig.1).

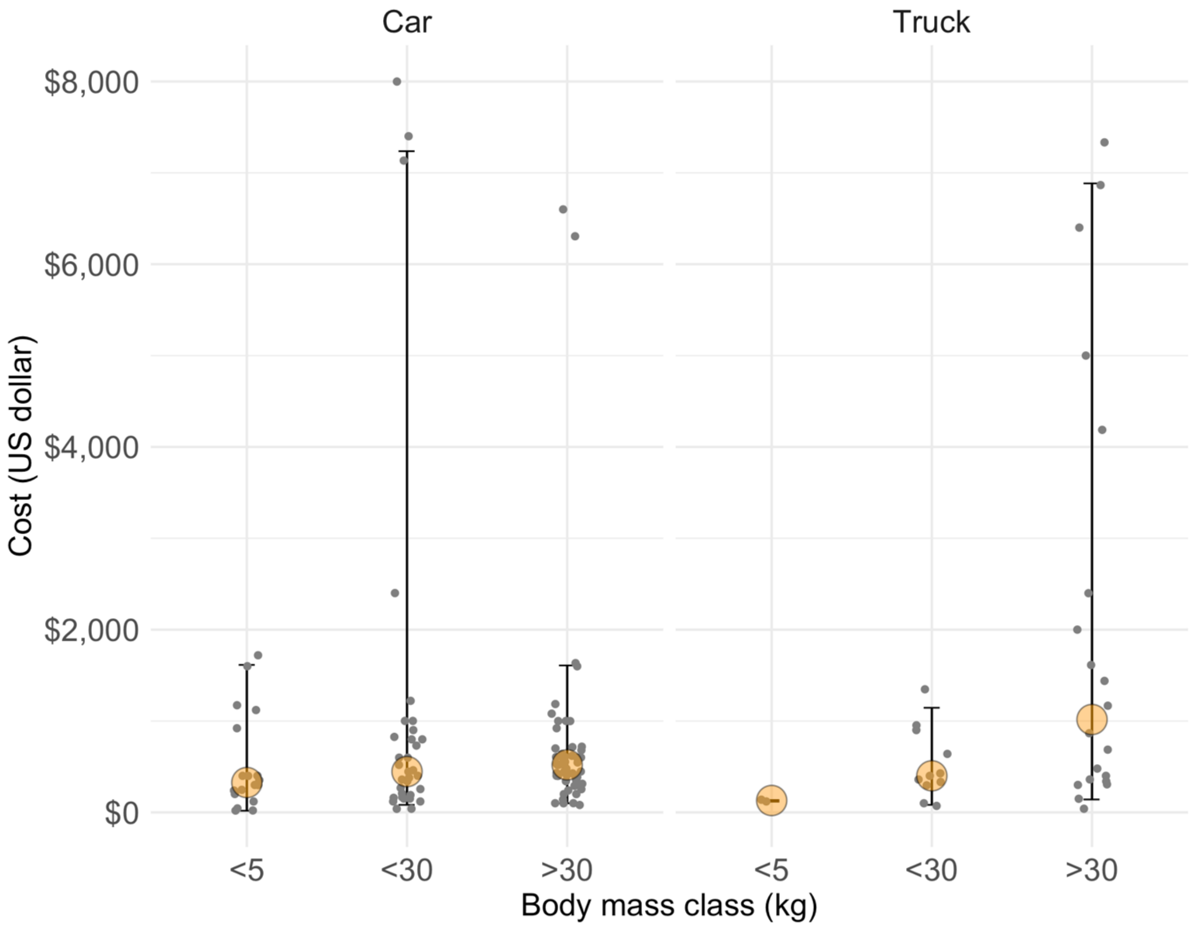


Figure 5 – Material costs from collisions with animals, by type of vehicle (truck and car) and animal body mass class (<5, <30, >30 kg). Big circles represent the median values of data collected (represented by the smaller dots, jittered to enable reading). Bars indicate 5-95% quantile range.

Tables

Table 1 – Summary information of transects surveyed searching for roadkill, indicating the length of transects in km, first date of survey, number of surveys, daily traffic volume, and the proportion (%) of cars and trucks in traffic volume. Traffic volume was obtained from official counts (DNIT 2020), except for MS040 and MS338 which was assessed by the team using the same methodology of DNIT (2020). For R3A we assumed the same traffic characteristics as R2 (contiguous and similar roads). BR262 and BR267 are federal roads, and MS040 and MS338 are state roads.

Transect ID	**Road name**	**Length (km)**	**First systematic survey**	**Number of Surveys**	**Daily Traffic Volume (median)**	**Trucks (%)**	**Cars (%)**
R1A	BR262	182	06/02/2017	78	3,633	39	59
R1B	BR262	129	07/02/2017	25	3,773	48	52
R2	MS040	224	07/02/2017	79	653*	37*	60*
R3A	MS338	66	07/02/2017	79	653*	37*	60*
R3B	BR267	218	27/02/2017	79	3,973	46	49
R4	BR262	339	29/03/2017	80	3,098	33	77

Table 2 – Survey effort for carcass persistence experiments: length of transects, number of daily surveys per season, and number of carcasses surveyed per body mass class and season. Body mass classes: between 1-5 kg (<5), between 5-30 kg (<30) and more than 30 kg (>30).

Transect ID	**Length (km)**	**Surveys Wet / Dry**	**Body mass Class (kg)**	**Carcasses Wet / Dry**	**Total carcasses**
R2	139	29 / 15	<5	66 / 13	79
			<30	24 / 20	44
			>30	8 / 3	11
R3B	96	0 / 15	<5	- / 5	5
			<30	- / 9	9
			>30	- / 1	1
R4	107	21 / 30	<5	72 / 112	184
			<30	26 / 45	71
			>30	11 / 8	19
Total				**207 / 216**	**423**

Table 3 – Estimated total costs associated with animal-vehicle collisions with large animals (>1kg), and per km and year (includes costs from collisions of animals with cars and trucks). All costs in US$. Return period is the expected time in years for the accumulated costs from material damage to match up the initial investment. Estimates are given for the full transect length in top table and for the hotspots of mortality in bottom table. Range values result from the different scenarios using Search Efficiency and Search Area of 0.95 (lower costs, higher period values) and Search Efficiency of 0.85 and Search Area of 0.80 (higher costs, smaller period values).

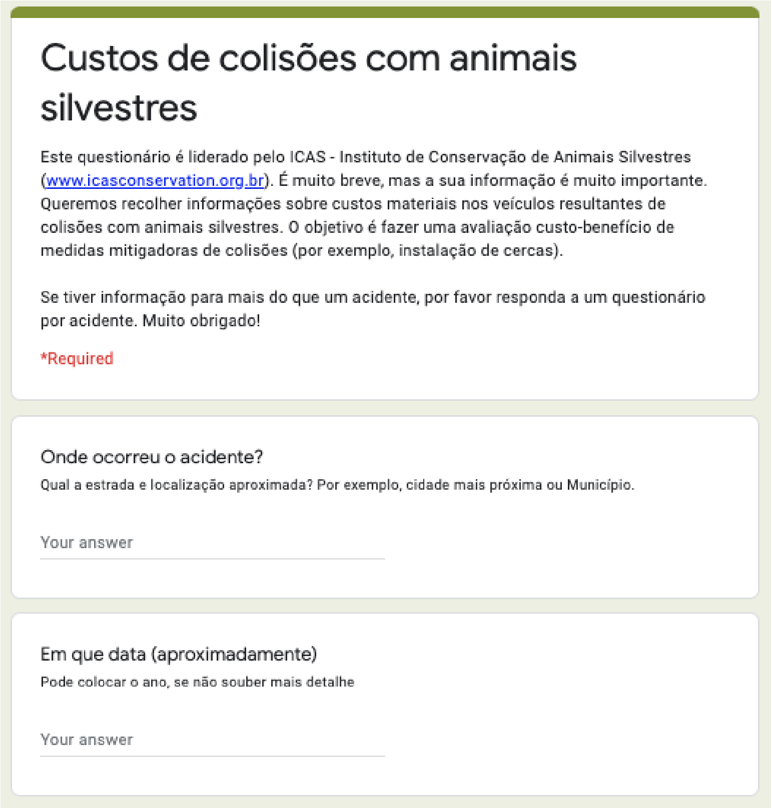
Transect ID	**Total cost (range)**	**Cost per km per year (range)**	**Return period**
Fencing the full transects			
R1A	664,222 - 857,192	1,170 - 1,510	29 - 23
R1B	122,275 - 158,151	948 - 1,226	36 - 28
R2	876,854 - 1,117,907	1,239 - 1,579	27 - 22
R3A	178,492 - 232,135	856 - 1,113	40 - 31
R3B	765,291 - 950,688	1,111 - 1,380	31 - 25
R4	1,848,596 - 2,328,935	1,704 - 2,147	20 - 16
Fencing the hotspot sections			
R1A	211,375 - 272,806	1,936 - 2,498	18 - 14
R1B	19,350 - 25,037S	1,935 - 2,504	18 - 14
R2	267,980 - 341,693	2,120 - 2,703	16 - 13
R3A	63,612 - 82,632	1,342 - 1,743	25 - 20
R3B	150,295 - 186,859	1,902 - 2,365	18 - 14
R4	880,873 - 1,109,752	3,059 - 3,853	11 - 9

Supplementary material

S1 - Google form

The form can be found in the following URL:

https://docs.google.com/forms/d/1fZ57Y8IJcARRKKzm7uOqDPAJN69VkQFF5cJmuxz41xk/edit



Custos de colisões com animais silvestres

Este questionário é liderado pelo ICAS - Instituto de Conservação de Animais Silvestres (www.icasconservation.org.br). É muito breve, mas a sua informação é muito importante. Queremos recolher informações sobre custos materiais nos veículos resultantes de colisões com animais silvestres. O objetivo é fazer uma avaliação custo-benefício de medidas mitigadoras de colisões (por exemplo, instalação de cercas).

Se tiver informação para mais do que um acidente, por favor responda a um questionário por acidente. Muito obrigado!

*Required

Onde ocorreu o acidente?

Qual a estrada e localização aproximada? Por exemplo, cidade mais próxima ou Município.

Your answer

Em que data (aproximadamente)

Pode colocar o ano, se não souber mais detalhe

Your answer

Fig. S1.1 – Snapshot of the first questions in Portuguese of the Google form asking about the date, place and period of the day (day, night, sunset, sunrise) of the collision events; the type of vehicle (car, truck, other); name or description of the species involved in collisions; and the cost of the material damage, if any.

S2 – Roadkill summary information

Table S2.1 – Summary of roadkill recorded by number (N), body mass class, and the likelihood of causing material damage in vehicles when involved in collisions (Damage). Taxa are sorted according to BM and alphabetic order. Body mass classes: between 1-5 kg (<5), between 5-30 kg (<30) and more than 30 kg (>30).

Class	**Species / *taxa***	**N**	**Body mass**	**Damage**
Amphibians	Amphibians	203	<0.1	no
Reptiles	Reptiles <1kg	68	<1	no
	Boiruna maculata	1	<5	no
	Bothrops moojeni	2	<5	no
	Dracaena paraguayensis	18	<5	no
	Drymarchon corais	1	<5	no
	Iguana iguana	13	<5	no
	Palusophis bifossatus	1	<5	no
	Spilotes pullatus	2	<5	no
	Other reptiles <5kg	204	<5	no
	Boa constrictor	34	<30	no
	Crotalus durissus	13	<30	no
	Eunectes notaeus	72	<30	no
	Hydrodynastes gigas	25	<30	no
	Paleosuchus palpebrosus	1	<30	no
	Salvator merianae	246	<30	no
	Other reptiles <30kg	10	<30	no
	Caiman latirostris	35	>30	no
	Caiman yacare	849	>30	no
	Eunectes murinus	16	>30	no
	Other reptiles >30kg	10	>30	no
Birds	*Ammodramus humeralis*	1	<0.1	no
	Brotogeris chiriri	6	<0.1	no
	Campylorhamphus trochilirostris	1	<0.1	no
	Columbina talpacoti	1	<0.1	no
	Crotophaga ani	26	<0.1	no
	Eupsittula aurea	47	<0.1	no
	Icterus croconotus	1	<0.1	no
	Myiozetetes similis	1	<0.1	no
	Nyctidromus albicollis	6	<0.1	no
	Nystalus chacuru	1	<0.1	no

Class	Species / *taxa*	N	Body mass	Damage
	Paroaria capitata	6	<0.1	no
Birds (cont.)	*Passer domesticus*	2	<0.1	no
	Patagioenas picazuro	1	<0.1	no
	Pitangus sulphuratus	17	<0.1	no
	Polytmus guainumbi	1	<0.1	no
	Sicalis flaveola	1	<0.1	no
	Taraba major	1	<0.1	no
	Thamnophilus doliatus	4	<0.1	no
	Trogon curucui	1	<0.1	no
	Turdus rufiventris	1	<0.1	no
	Tyrannus melancholicus	2	<0.1	no
	Xolmis velatus	2	<0.1	no
	Other birds <0.1kg	158	<0.1	no
	Alipiopsitta xanthops	2	<1	no
	Amazona aestiva	15	<1	no
	Amazona amazonica	1	<1	no
	Aramides cajanea	7	<1	no
	Aratinga nenday	2	<1	no
	Athene cunicularia	59	<1	no
	Campephilus melanoleucos	1	<1	no
	Colaptes campestris	12	<1	no
	Columba livia	1	<1	no
	Crotophaga ani	26	<1	no
	Crotophaga major	2	<1	no
	Crypturellus parvirostris	1	<1	no
	Cyanocorax chrysops	4	<1	no
	Cyanocorax cyanomelas	1	<1	no
	Dendrocygna viduata	1	<1	no
	Falco sparverius	7	<1	no
	Guira guira	49	<1	no
	Heterospizias meridionalis	3	<1	no
	Jacana jacana	1	<1	no
	Megaceryle torquata	2	<1	no
	Megascops choliba	5	<1	no
	Melanerpes candidus	3	<1	no
	Myiopsitta monachus	1	<1	no
	Nothura maculosa	4	<1	no

Class	**Species / *taxa***	**N**	**Body mass**	**Damage**
	Nyctibius griseus	2	<1	no
Birds (cont.)	*Ortalis canicollis*	15	<1	no
	Piaya cayana	12	<1	no
	Primolius auricollis	1	<1	no
	Psittacara leucophthalmus	2	<1	no
	Pteroglossus castanotis	5	<1	no
	Ramphastos toco	32	<1	no
	Rhynchotus rufescens	24	<1	no
	Rupornis magnirostris	10	<1	no
	Tigrisoma lineatum	1	<1	no
	Tyto alba	12	<1	no
	Zenaida auriculata	1	<1	no
	Other birds <1kg	583	<1	no
	Aburria cumanensis	1	<5	no
	Ara ararauna	4	<5	no
	Ara chloropterus	1	<5	no
	Aramus guarauna	6	<5	no
	Cairina moschata	1	<5	no
	Caracara plancus	303	<5	no
	Cariama cristata	273	<5	no
	Cathartes aura	2	<5	no
	Cathartes burrovianus	2	<5	no
	Coragyps atratus	63	<5	no
	Crax fasciolata	2	<5	no
	Geranoaetus albicaudatus	2	<5	no
	Other birds <5kg	42	<5	no
	Rhea americana	20	<30	**yes**
Mammals	Mammals <1kg	42	<1	no
	Alouatta caraya	6	<5	**yes**
	Cabassous unicinctus	67	<5	no
	Chironectes minimus	2	<5	**yes**
	Dasyprocta azarae	44	<5	**yes**
	Dasypus novemcinctus	723	<5	no
	Dasypus septemcinctus	1	<5	no
	Didelphis albiventris	37	<5	**yes**
	Eira barbara	29	<5	**yes**
	Euphractus sexcinctus	1831	<5	no

Class	**Species / *taxa***	**N**	**Body mass**	**Damage**
	Herpailurus yagouaroundi	8	<5	**yes**
Mammals (cont.)	*Leopardus braccatus*	2	<5	**yes**
	Leopardus wiedii	1	<5	**yes**
	Lycalopex vetulus	52	<5	**yes**
	Nasua nasua	100	<5	**yes**
	Sapajus cay	4	<5	**yes**
	Sylvilagus brasiliensis	16	<5	**yes**
	Tamandua tetradactyla	549	<5	**yes**
	Other mammals <5kg	251	<5	no
	Cerdocyon thous	1614	<30	**yes**
	Chrysocyon brachyurus	16	<30	**yes**
	Cuniculus paca	3	<30	**yes**
	Leopardus pardalis	14	<30	**yes**
	Lontra longicaudis	9	<30	**yes**
	Mazama americana	6	<30	**yes**
	Mazama gouazoubira	33	<30	**yes**
	Myrmecophaga tridactyla	608	<30	**yes**
	Pecari tajacu	5	<30	**yes**
	Procyon cancrivorus	135	<30	**yes**
	Speothos venaticus	3	<30	**yes**
	Other mammals <30kg	95	<30	no
	Blastocerus dichotomus	7	>30	**yes**
	Hydrochoerus hydrochaeris	578	>30	**yes**
	Panthera onca	1	>30	**yes**
	Priodontes maximus	3	>30	**yes**
	Puma concolor	6	>30	**yes**
	Sus scrofa	11	>30	**yes**
	Tapirus terrestris	267	>30	**yes**
	Tayassu pecari	19	>30	**yes**

S3 - Suggested fence characteristics

In this study, the fences are the main measures discussed to be adopted, properly linked to existing road passages. In the studied transects there are several underpasses, including cattle boxes, drainage culverts and bridges. In R2 alone, there are 47 underpasses (39 cattle boxes and 8 bridges). Livestock management between roadsides is performed under the road, in large concrete structures with dimensions ≥ 2 x 2 meters. Such structures allow the crossing of wild animals, including large ones such as tapir, giant anteater and deer species.

Fences must prevent medium and large wild animals from entering the road. They should be at least 1.70 meters high and 30 cm buried in the ground, have a concrete wall or fiber cement screen in the lower part of the fence in contact with the ground and metallic wire mesh up to 10 x 10 cm and metal or concrete posts (Fig. S3.1). This design is recommended to bar the entry of animals that try to pass between the fence lines (e.g *Leopardus* sp.), jump over the fence (e.g. *Mazama gouazoubira*, *Mazama americana*, *Ozotoceros bezoarticus*), dig under the fence (e.g. *Dasypus* sp., *Euphractus sexcinctus, Priodontes maximus*) or that have enough strength to trying to push into the fence (e.g. *Hydrochoerus hidrochoerus, Tapirus terrestris*). Yet, the recommended design may only discourage climbing animals from overcoming the fence, but not completely bar their entrance to the highway (e.g. *Nasua nasua, Didelphis* sp.).

The cost of this fence type averages US$ 34,056 per km (in both sides), a value that was obtained from three companies that apply fences on MS roads (values in US$: 44,280, 31,680 and 26,208).

Figure S3.1 – The design of fence projected as a mitigation to decrease WVC (A), and in combination with wildlife underpasses, water culverts or cattle boxes (B). Source: ViaFAUNA Environmental Studies.

S4 - Carcass persistence probability models

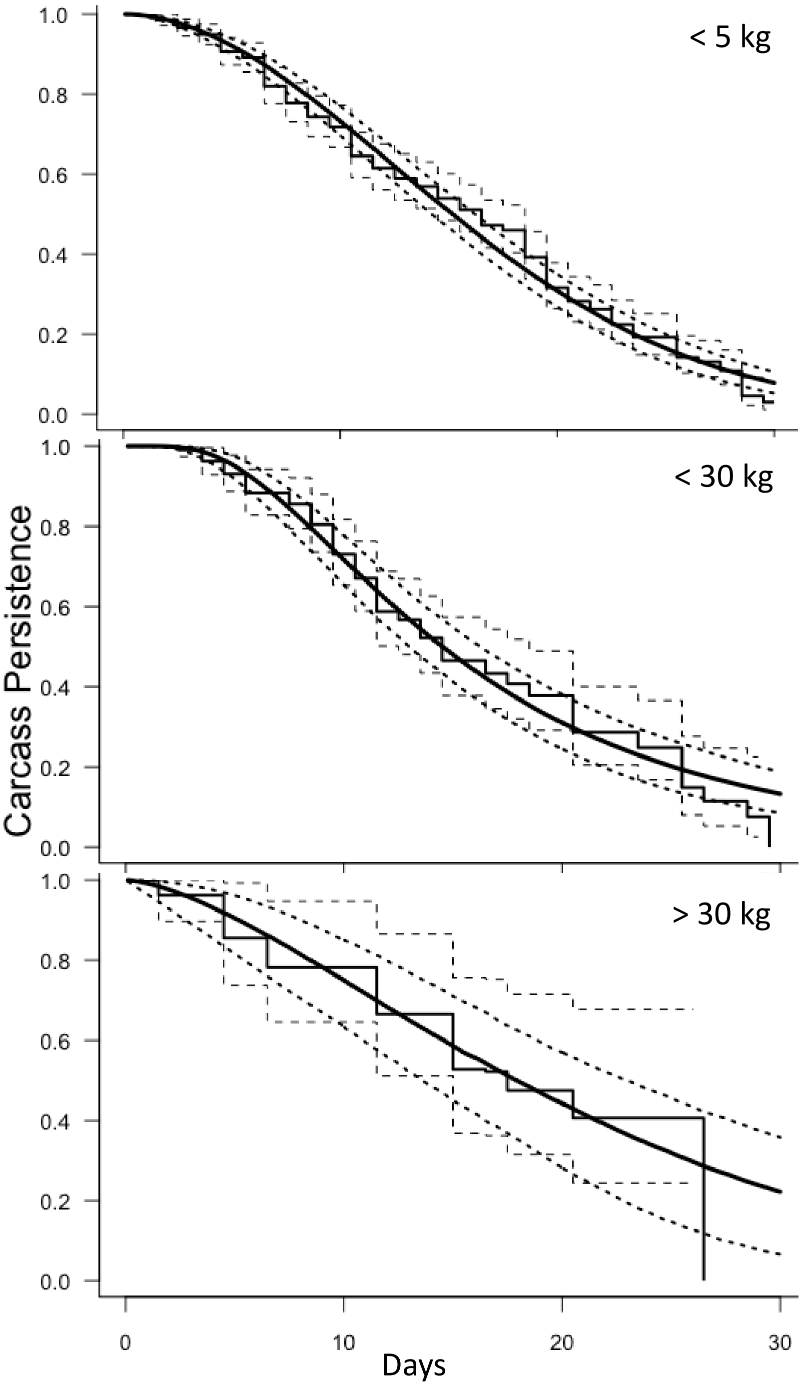


Fig S4.1 - Carcass persistence probability with time (days), per body mass class. Stair-shape line is the Kaplan Meier estimator, continuous line is the Weibull distribution fitted to data. Respective confidence intervals are plotted in dotted line. Dotted blue lines indicate the median persistence probability for the time interval of systematic surveys.