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MAMMAL ROAD MORTALITY AND COST–BENEFIT ANALYSES OF MITIGATION MEASURES AIMED AT REDUCING COLLISIONS WITH CAPYBARA (*Hydrochoerus hydrochaeris*) IN SÃO PAULO STATE, BRAZIL

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ABSTRACT

We recorded 26 mammal species or species groups as roadkill along seven highways in São Paulo State, Brazil. Capybara (*Hydrochoerus hydrochaeris*)-vehicle collisions were the most frequently reported species and, because of their size and weight, they can cause substantial vehicle damage and are a serious threat to human safety. Other roadkilled species such as maned wolf (*Chrysocyon brachyurus*), giant anteater (*Myrmecophaga tridactyla*) and oncilla (*Leopardus tigrinus*) indicate there may also be a conservation concern that could warrant the implementation of mitigation measures aimed at reducing wildlife-vehicle collisions and providing safe crossing opportunities. For this paper we investigated a potential third argument for the implementation of mitigation measures: economics. We calculated vehicle repair costs associated with capybara-vehicle collisions based on interviews with personnel from car repair shops. In addition, we reviewed the effectiveness of wildlife fencing in combination with wildlife crossing structures in reducing collisions with large mammals. We then estimated the costs for four mitigation measures (fencing with and without three types of culverts). These data were used to conduct cost-benefit analyses over a 75-year period using discount rates of 1%, 3%, and 7% to identify the threshold values (in 2012 R$) above which the four individual mitigation measures start generating benefits in excess of costs. These threshold values were translated into the number of capybara-vehicle collisions that need to occur per kilometer per year for a mitigation measure to start generating economic benefits in excess of costs. For example, based on an analysis with average vehicle repair costs and a 3% discount rate, we calculated that with at least 5.4 capybara-vehicle collisions per kilometer per year, a combination of wildlife fencing and any of the three culvert types would be economically feasible. In addition, we calculated the total costs associated with capybara-vehicle collisions on seven major highways in São Paulo State, Brazil, and we compared these to the threshold values. Finally, we conducted more detailed cost analyses for the seven highways to illustrate that even though the costs for capybara-vehicle collisions may not justify the implementation of measures along an entire highway, specific locations along a highway can still exceed thresholds. We believe the cost-benefit model presented in this paper can be a valuable decision support tool to help select locations and implement mitigation measures. These measures improve human safety, are likely to benefit nature conservation, and are economically justified even based on very conservative cost-benefit analyses. We do stress though that the threshold values presented in this paper are based on a series of assumptions and estimates and that they should be taken as indicative values rather than exact values.
Keywords: Fence; road mortality; road ecology; underpass; wildlife-vehicle collisions.

RESUMO

MORTALIDADE DE MAMÍFEROS EM RODOVIAS E ANÁLISE DE CUSTO-BENEFÍCIO DAS MEDIDAS DE MITIGAÇÃO PARA REDUÇÃO DE ATROPELAMENTOS COM CAPIVARAS (*Hydrochoerus hydrochaeris*) NO ESTADO DE SÃO PAULO, BRASIL. Foram registradas 26 espécies de mamíferos mortos por atropelamento ao longo de sete rodovias do Estado de São Paulo, Brasil. As colisões

entre veículos e capivaras (*Hydrochoerus hydrochaeris*) foram as mais frequentes e, por seu tamanho e peso, essa espécie pode causar danos graves aos veículos e ser uma ameaça para a segurança do usuário. Outras espécies mortas em rodovias como o lobo guará (*Chrysocyon brachyurus*), tamanduá bandeira (*Myrmecophaga tridactyla*) e o gato do mato (*Leopardus tigrinus*) indicam que também pode haver preocupação com a conservação, o que deve garantir a implantação de medidas de mitigação destinadas a reduzir as colisões entre veículos e animais e gerar oportunidades de travessias em segurança. Para este artigo, investigamos um terceiro argumento potencial para as medidas de mitigação: a economia. Calculamos os custos de reparação de veículos associados com colisões com capivaras baseados em entrevistas com funcionários de oficinas automotivas. Além disso, foi revisada a efetividade de cercamento em combinação com passagens de fauna para reduzir as colisões com grandes mamíferos. Posteriormente, estimamos os custos de quatro medidas de mitigação (cercamento, com e sem, três tipos de tubos/dutos). Esses dados foram usados para conduzir as análises de custo-benefício em um período de 75 anos, usando taxas de descontos de 1%, 3% e 7% para identificar os valores-limite (em reais em 2012) a partir dos quais as quatro medidas de mitigação começam a gerar benefícios ao invés de custos. Estes valores foram traduzidos em termos do número de colisões entre veículos e capivaras por quilômetro por ano a partir do qual a medida de mitigação retorna benefícios ao invés de custos. Por exemplo, em uma análise com base no custo médio de reparação e uma taxa de desconto de 3%, estima-se que a partir de 5,4 colisões de capivaras por km por ano, a combinação de cercamento com qualquer um dos três tipos de passagens de fauna seria economicamente viável. Além disso, estimamos os custos totais associados de colisões com capivaras em sete das principais rodovias do Estado de São Paulo, Brasil, e comparamos isso com os valores-limite. Finalmente, conduzimos análises mais detalhadas para as sete rodovias a fim de ilustrar que, embora os custos das colisões não justifiquem a implementação de medidas em toda a extensão da rodovia, a seleção de locais específicos poderia exceder os valores-limite. Acreditamos que os modelos de custo-benefício apresentados podem ser uma ferramenta de tomada de decisão importante para ajudar a selecionar locais e implementar medidas para melhorar a segurança do usuário. Estas medidas podem beneficiar a conservação da biodiversidade e são economicamente justificadas, mesmo em cenários conservadores de custo-benefício. Ressalta-se, contudo, que os valores de limite mostrados baseiam-se em um número de suposições e estimativas e devem ser tomados como valores indicativos, e não como valores exatos.
Palavras-chave: Cercamento; atropelamento em rodovias; ecologia de estradas; passagem inferior de fauna; colisões entre veículos e animais.

RESUMEN

MORTALIDAD EN CARRETERA DE MAMÍFEROS Y ANÁLISIS DE COSTO-BENEFICIO DE LAS MEDIDAS DE MITIGACIÓN PARA REDUCIR LAS COLISIONES CON CAPIBARAS (*Hydrochoerus hydrochaeris*) EN EL ESTADO DE SÃO PAULO, BRASIL. Registramos 26 especies o grupos de especies de mamíferos muertos en carretera a lo largo de siete carreteras del estado de São Paulo, Brasil. Las colisiones entre vehículos y capibaras (*Hydrochoerus hydrochaeris*) fueron las más frecuentes y, por su tamaño y peso, éstas pueden causar daños sustanciales a los vehículos, y ser una amenaza para la seguridad humana. Otras especies muertas en carretera como el aguará guazú (*Chrysocyon brachyurus*), el oso hormiguero gigante (*Myrmecophaga tridactyla*) y el tigrillo (*Leopardus tigrinus*) indican que puede haber una preocupación con la conservación, que debe garantizar la implementación de medidas de mitigación destinadas a reducir las colisiones entre vehículos y animales y generar oportunidades para atravesar con seguridad. Para este artículo, investigamos un potencial tercer argumento para las medidas de mitigación: la economía. Calculamos los costos de reparación de vehículos asociados con colisiones con capibaras basados en entrevistas con el personal de talleres de reparación. Adicionalmente, revisamos la efectividad de barreras en combinación con estructuras para el cruce de la vida silvestre para reducir las colisiones con grandes mamíferos. Posteriormente estimamos los costos de las cuatro medidas de mitigación (barreras con y sin tres tipos de ducto). Estos datos fueron usados para conducir análisis de costo-beneficio en un período de 75 años, usando tasas de descuento de 1%, 3%, y 7% para identificar los valores umbral (en reales de 2012) a partir de los cuales las cuatro medidas de mitigación comienzan a generar beneficios en vez de costos. Estos valores

fueron traducidos en términos del número de colisiones vehículo-capibara por kilómetro por año a partir del cual la medida de mitigación retorna beneficios en vez de costos. Por ejemplo, basados en un análisis con el costo medio de la reparación y una tasa de descuento del 3%, calculamos que a partir de 5,4 colisiones con capibaras por kilómetro por año, una combinación de barreras a la vida silvestre y uno de los tres tipos de paso sería viable económicamente. Adicionalmente, calculamos los costos totales asociados con colisiones con capibaras en siete carreteras principales en el estado de São Paulo, Brasil, y los comparamos con los valores umbral. Finalmente, condujimos análisis más detallados para las siete carreteras para ilustrar que, aunque los costos de las colisiones no justifiquen la implementación de medidas a lo largo de toda una carretera, localidades específicas a lo largo de éstas pueden exceder los umbrales. Creemos que los modelos de costo-beneficio presentados pueden ser una herramienta de toma de decisión valiosa para ayudar a seleccionar localidades e implementar medidas para mejorar la seguridad humana. Estas medidas pueden beneficiar la conservación y son justificadas económicamente aún en escenarios muy conservadores de costo-beneficio. Resaltamos, sin embargo, que los valores umbral presentados están basados en una serie de supuestos y estimados y deben ser tomados como estimativas y no como valores exactos.
Palabras clave: Barrera; mortalidad en carretera; ecología de carreteras; ecoductos; colisiones entre vehículos y animales.

INTRODUCTION

Wildlife-vehicle collisions are numerous around the world and affect human safety, property and wildlife. In North America and Europe most of the road-kill studies and mitigation efforts are directed at large mammals, specifically ungulates, which are relatively numerous and also large enough to pose a substantial threat to human safety (Conover *et al.* 1995, Romin & Bissonette 1996, Groot Bruinderink & Hazebroek 1996, Huijser *et al.* 2009). Other road-kill studies and mitigation efforts tend to focus on species whose population survival probability is severely affected by roads and traffic (e.g. Mansergh & Scotts 1989, van der Ree *et al.* 2009).

Over 40 types of mitigation measures aimed at reducing collisions with large mammals have been described (see reviews in Hedlund *et al.* 2004, Knapp *et al.* 2004, Huijser *et al.* 2008). Examples include warning signs that alert drivers to potential animal crossings, wildlife warning reflectors or mirrors (e.g. Reeve & Anderson 1993, Ujvári *et al.* 1998), wildlife fences (Clevenger *et al.* 2001), and animal detection systems (Huijser *et al.* 2006). However, the effectiveness and costs of these mitigation measures vary greatly (Huijser *et al.* 2009). Wildlife fencing in combination with wildlife crossing structures is generally considered the most effective and robust way to reduce collisions with large mammals while still allowing the animals to cross safely under or over the road (Huijser *et al.* 2009).

Most highway mitigation measures are implemented because of concerns for human safety or conservation (e.g. threatened or endangered species) (Huijser *et al.* 2009). In this paper we investigate which mammal species are hit most frequently by vehicles along seven major highways in São Paulo State, Brazil. We were particularly interested in capybara (*Hydrochoerus hydrochaeris*). Capybaras are the world's largest rodent and adults stand about 50 cm tall and can weigh around 54 kg (males) -62 kg (females) (Eisenberg & Redford 1999, Ferraz *et al.* 2005). These rodents of unusual size are considered food and habitat generalists, have high reproductive capacity, and combined with a decline of large predators, they can reach high population densities in anthropogenic landscapes, including the central region of São Paulo State (Verdade & Ferraz 2006, Garcias & Bager 2009). Because of the size and weight of capybara and their abundance, collisions with vehicles are a serious concern. Not only do they result in substantial damage to vehicles but they can also affect human safety (Em 2011, OGLOBO 2011, UOL Notícias 2011).We were also interested in potential threatened or endangered species that may have been reported as roadkill as they may require mitigation based on concerns for nature conservation rather than human safety.

In addition we conducted cost-benefit analyses for mitigation measures aimed at reducing collisions with capybara. We hypothesized that, similar to ungulates in North America (e.g. Reed *et al.*1982, Huijser *et al.* 2009), the costs associated with capybara-vehicle collisions on certain road sections may be greater than the costs associated with implementing mitigation measures aimed at keeping capybara from accessing the highway and at providing safe crossing opportunities. This would then provide an important third argument to implement highway-wildlife mitigation measures in Brazil and specifically in São Paulo State; mitigation measures not only benefit human safety and nature conservation but they can also be a wise economic investment.

METHODS

CARCASS REMOVAL DATA

We obtained carcass removal data from six 4-lane highways and one 2-lane highway in São Paulo State (Table I) (ARTESP 2012). The highways are toll roads and the organizations responsible for the operation and maintenance check the entire length of the highways every few hours for potential problems (e.g. stranded motorists, debris [including road-killed animals]on road). The road maintenance crews recorded the date, species, number and location of the road-killed animals to the nearest 0.1km or 1.0km (Table I). The provider of the data did not allow us to display the highway names or numbers. Therefore we coded the seven highways with capital letters (A through G) throughout this paper. We also set the start point for each of the seven highways at 0.0km regardless of the actual km markers located along the highways to avoid revealing the highways and locations along the highways.

The database for the first six highways (A through F) also included many other species besides capybara. To obtain insight in the numbers of other species killed on these highways we not only summarized the number of reported carcasses for capybara but also for all other mammal species that were present in the database and noted the IUCN red list status for the individual species (IUCN 2012), and the conservation status in Brazil (MMA 2008) and São Paulo State (SMA 2009).

Table I. The seven highways in São Paulo State included in our analyses with the years we used the mammal carcass data for, the length of the highway segments that were monitored, the spatial resolution of the carcass removal data, and the frequency of checks for road-killed animals.

Hwy	Lanes (n)	Start date	End date	Length (km)	Spatial reso-lution (km)	Frequency road checks
A	4	1 Jan 2005	31 Dec 2011	142	0.1	Every 3 hrs
B	4	1 Jan 2005	31 Dec 2011	80	0.1	Every 3 hrs
C	4	1 Jan 2005	31 Dec 2010	43	0.1	Every 3 hrs
D	4	1 Jan 2005	31 Dec 2010	76	0.1	Every 3 hrs
E	4	1 Jan 2005	31 Dec 2010	76	0.1	Every 3 hrs
F	4	1 Jan 2005	31 Dec 2010	122	0.1	Every 3 hrs
G	2	1 Jan 2010	31 Oct 2010	247	1.0	Every 1.5 hrs

MITIGATION MEASURES FOR CAPYBARA

We evaluated four different mitigation measures or combinations of mitigation measure+s in our cost-benefit analyses for capybara:

- Chain-link fencing (1.5m high) with concrete posts. This type of fencing is considered a barrier to capybara. This fence looks similar to that in Figure 1, but without the concrete bottom/foundation. Instead the chain-link fence extends to the ground.
- Fencing (see above) with 1.70m diameter culverts (Figure 2) and wildlife jump-outs (for photo see Huijser *et al*., 2009). Jump-outs are earthen ramps that allow animals that are trapped in between the fences in the road corridor to walk up to the top

of the fence and jump down to safety. Well-designed jump-outs are low enough to allow animals to jump to safety, and high enough to discourage them from jumping up into the road corridor. While we do not know if capybara use jump-outs we did include these escape opportunities in the mitigation.

- Fencing (see above) with 2.00m diameter culverts and wildlife jump-outs.
- Fencing (see above) with 3.00x3.00m box culverts (Figure 3) and wildlife jump-outs.

Figure 1. An example of the 1.5m high chain-link capybara fence evaluated for the cost-benefit analyses (Copyright © 2011, by Manetoni). Note that the fence in the photo shows a concrete bottom/foundation. For our cost-benefit analyses we did not include this concrete foundation; instead the chain-link fence extended to the ground.

Figure 2. An example of a 1.7m diameter culvert under a highway evaluated for the cost-benefit analyses (Copyright © 2012, by Fernanda D. Abra).

Figure 3. An example of a box culvert under a highway evaluated for the cost-benefit analyses (Copyright © 2012, by Fernanda D. Abra). Note that this particular culvert measures 2.00x2.00m and that we evaluated a culvert that is 3.00x3.00m.

The fencing is considered a substantial barrier to capybara and all three types and dimensions of culverts are considered suitable for capybara (Abra 2012). We estimated the fencing, with or without culverts, to reduce capybara-vehicle collisions by 86 % based on other studies for large mammals: Reed *et al.* (1982) 79%; Ward (1982): 90% Woods (1990): 94-97%; Clevenger *et al.* (2001): 80%; Dodd *et al.* (2007): 87%).

Wildlife fencing alone increases the barrier effect of roads and traffic and causes further habitat fragmentation. To avoid this unintended consequence of fencing it is considered good practice to not increase the barrier effects of roads and traffic (e.g. through fencing) without also providing for safe crossing opportunities for wildlife (e.g. through wildlife underpasses and overpasses). It is also considered good practice to provide escape opportunities (e.g. wildlife jump-outs) for animals that do end up in the fenced road corridor. While we did include fencing as a stand-alone mitigation measure in our cost-benefit analyses we discourage the implementation of fencing without also providing for safe crossing opportunities for wildlife and a means to escape from the fenced road corridor. Connectivity across roads for wildlife is also in the interest of human safety as animals are more likely to break through a barrier (e.g. wildlife fencing) if safe crossing opportunities are not provided or if they are too few, too small, or too far apart.

COST ESTIMATES CAPYBARA-VEHICLE COLLISIONS

We estimated the average vehicle repair costs as a result of a collision with capybara based on interviews with employees of car repair shops in the area around the city of São Paulo in June 2012. We only included vehicle repair costs in our estimates as we were unable to obtain data on the costs associated with the occasional human injuries and human fatalities, towing, accident attendance and investigation, and the cost of disposal of the animal carcass. Passive use costs were also not included in our cost-benefit analyses. Since passive use costs are very unlikely to be zero, the benefit-cost results reported in this paper should be considered conservative. Passive or nonuse values are generally based on existence or bequest motives and include values in addition to those that arise directly due to the collision (Krutilla 1967, Daily *et al*. 1997). In this context, passive values could include the value individuals (even those who perhaps never drive the road section of interest) place on having viable populations of certain species and well-functioning ecosystems as a result of the reduced road mortality and a certain amount of connectivity for wildlife associated with a mitigation measure. For the case at hand, there are likely to be passive use values associated with at least some of the different mammal species or species groups reported as roadkill, especially for species that are considered near threatened (maned wolf) or vulnerable (giant anteater and oncila).

We asked the employees of ten car repair shops for their minimum and maximum cost estimates for vehicle repair as a result of a collision with capybara. The personnel based their estimates on their experiences with repairs on one of the most popular cars in Brazil: Volkswagen Gol. The average for the minimum was R$ 1,720 and the average for the maximum was R$ 4,050 (Table II). We then calculated the average of the maximum and minimum estimates for each car repair shop to estimate the average costs for the repair; R$ 2,885 (Table II).

Table II. Estimates for the minimum, maximum and average vehicle repair costs as a result of a collision of a Volkswagen Gol with capybara.

Car repair shop	Minimum estimate (R$)	Maximum estimate (R$)	Average estimate (R$)
1	1,200.00	4,000.00	2,600.00
2	2,500.00	5,000.00	3,750.00
3	2,000.00	4,000.00	3,000.00
4	1,200.00	4,000.00	2,600.00
5	2,000.00	4,500.00	3,250.00
6	1,500.00	3,500.00	2,500.00
7	1,500.00	3,000.00	2,250.00
8	1,800.00	4,000.00	2,900.00
9	2,000.00	5,000.00	3,500.00
10	1,500.00	3,500.00	2,500.00
Average	1,720.00	4,050.00	2,885.00

For our cost-benefit analyses we assumed that all collisions involving capybara resulted in vehicle damage and vehicle repair costs. However, collisions that result in no or minor damage may not cause the owner of the vehicle to have the damages repaired in a shop. This could mean that the costs for an average capybara-vehicle collision may be lower than the estimates derived from the interviews. On the other hand it is unlikely that all carcasses are observed and reported, which results in an underestimate of the costs associated with capybara-vehicle collisions along the various road segments. More importantly, some vehicles are smaller than the brand and model we based our estimates on and are therefore more likely to sustain more damage. However, larger vehicles, especially large trucks, may not sustain much damage at all. If and when better data are available on the costs associated with vehicle repairs and other costs associated with capybara-vehicle collisions it would allow for more precise cost-benefit analyses.

COST ESTIMATES MITIGATION MEASURES FOR CAPYBARA

We estimated the cost of the four different types and combinations of mitigation measures based on a review of the literature and interviews with researchers and transportation agency personnel (see Huijser *et al.* 2009; City of São Paulo 2012). The costs were calculated for a 4-lane motorway (2 lanes in each direction with a median) and standardized as costs per kilometer road length. Unless indicated otherwise, all cost estimates were expressed as R$ (Brazilian Real (BRL). We obtained costs for fencing and three different types of underpasses in 2012 R$. Other costs (operation, maintenance, removal, jump-outs) were based on Huijser *et al.* (2009). However, the US$ values were now made to be R$ values which essentially cut the cost estimates about in half (1 US$ was 2.03 R$ on 25 July 2012). We think this was justified and still conservative as we compared the costs of the culverts evaluated in these cost-benefit analyses to similar sized culverts in Montana and found the costs for the culverts in Brazil to be only about 27 % of the costs for the culverts in Montana. Therefore we argue that other construction and also operation, maintenance and removal costs are likely overestimated rather than underestimated when replacing the US$ with R$ and keeping the numbers the same, effectively putting these costs at about 50 % of the costs in North America.

The costs for the capybara fence was estimated at R$ 70 per meter - R$ 140,000 per km road length with fence on both sides of the road, and R$ 65-75 per meter depending on the road length that needs to be fenced (Manetoni 2011). The projected life span of this wildlife fence was set at 25 years. Fences require maintenance, for example as a result of fallen trees, vehicles that have run off the road and into the fence, and animals that may have succeeded digging under the fence (Clevenger *et al.* 2002). Therefore maintenance costs were set at R$ 500 per km per year and fence removal costs were set at R$ 10,000 per km road length.

For our cost benefit analyses we set the number of safe crossing opportunities at one per 2km (0.5 crossing opportunity per km). This number is based on the actual number of crossing structures found at three long road sections (two lanes in each travel direction) that have wildlife fencing and crossing structures for large animals: 24 crossing structures over 64km (0.38 structures per km) (Foster & Humphrey 1995); 24 crossing structures over 45km (0.53 structures per km) (Clevenger *et al.* 2002); and (17 crossing structures over 31km (0.56 structures per km) (Dodd *et al.* 2007). While it may require a different density of crossings to maintain viable wildlife populations in a landscape bisected by roads, a density of 0.5 crossing opportunities per km is based on actual practice which make our cost-benefit analyses most realistic.

For the purposes of our cost-benefit analyses for wildlife fencing in combination with safe crossing opportunities we distinguished between three types of culverts (Table III). The motorways we conducted the cost-benefit analyses for have two lanes in each direction with a median in between. We calculated the length of the culverts to be 35m. This allowed 17.5m of culvert for each travel direction (two lanes are typically 15-17 m wide).

Table III. The costs for the three types of culvert used in our cost-benefit analyses (based on City of São Paulo 2012).

Culvert type	Cost (R$/m)	Costs for one structure along 4-lane motorway (35 m culvert length) (R$)
1.70 m diameter culvert	R$ 805.92	R$ 28,207.20
2.00 m diameter culvert	R$ 1,162.57	R$ 40,689.95
3.00 m x 3.00 m box culvert	R$ 1,662.47	R$ 58,186.45

Maintenance and operation costs were estimated at RS $2,000 per structure per year (R$1,000 per km per year). The projected life span of an underpass was set at 75 years. Structure removal costs were estimated at R$ 30,000 per structure (R$ 15,000) per km. The length of the fence was not reduced because of the gap as a result of the crossing structure, as the fence is angled towards the road and ties in with the crossing structure. For our cost-benefit analyses we used jump-outs or escape ramps as escape opportunities for large animals. The reported costs for one jump-out are US$ 11,000 (US$ 13,200 in 2007 US$) (Bissonette & Hammer 2000) and US$ 6,250 (2006) (US$ 6,425 in 2007 US$) (Personal communication Pat Basting, Montana Department of Transportation). We set the costs for a jump-out at R$ 9,813 with a projected life span of 75 years. The number of escape ramps between crossing structures was set at 7 per roadside per 2km (2 immediately next to a crossing structure (50m on either side from the center of the structure), and an additional five escape ramps with 317m intervals (7 per km; R$ 68,691 per km). The escape ramps on either side of a crossing structure are required because of the continuous nature of the wildlife fencing and the assumption that animals will want to cross the road most often at the location of the crossing structures, as that should be one of the most important criteria for the placement of these crossing structures.

COST-BENEFIT ANALYSES FOR CAPYBARA

We based our cost-benefit analyses on the model we presented in an earlier paper (Huijser *et al.* 2009).

We refer to this previous paper for full details on our cost-benefit analyses, including formula. Here we only present the main structure and the most important assumptions of the cost-benefit model.

We conducted the cost-benefit analyses over a 75-year period. The costs included design, construction or implementation, maintenance, and removal efforts. The 75-year period is equal to the longest lifespan of the mitigation measures reviewed (i.e. concrete culverts). In the 75th year, no new investments were projected (only maintenance and removal costs). Fencing and culverts take considerable planning and installation time. Therefore we did not project any benefits in the first year of the cost–benefit analyses.

For our cost–benefit analyses, all costs and benefits are in Brazilian Real (R$, BRL) (i.e. constant 2012 R$). Accordingly, as we excluded inflation effects in our benefit and cost streams over time, we also used real (as opposed to nominal) discount rates. The typical pattern for the mitigation measures we examined is that costs are largely construction oriented in the present (e.g. an investment in a fence with a culvert in the first year of a 75-year period) whereas benefits are distributed more uniformly over the life of the project (i.e. a certain reduction in collisions and associated costs each year). In this situation, the cost–benefit analysis is sensitive to the discount rate chosen. The discount rate simply corrects for the time value of money. We conducted the analyses for real discount rates of 1 %, 3 %, and 7 %. We consider the 1 % and 3 % discount rate more appropriate than the 7 % discount rate that is required by some governments as the investments and returns span multiple generations (75 years) (U.S. OMB 1992; U.S. Environmental Protection Agency 2000, Weitzman 2001, Sumaila & Walters 2005).

After estimating the costs for each of the four mitigation measures, and after correcting for the discount rate, we calculated how much benefit (in 2012 R$) each mitigation measure needs to generate over a 75-year period in order to break even and have the benefits exceed the costs (threshold values). We then translated this threshold in the number of capybara-vehicle collisions that need to occur per kilometer per year for the four different mitigation measures to break even. We not only distinguished between three different discount rates (1 %, 3 % and 7 %), but we also conducted separate analyses based on the estimated minimum, average and maximum vehicle repair costs (see earlier in methods).

Note that the results of our economic analyses apply to Brazil (specifically São Paulo State), but not necessarily to other countries or regions, because we used species characteristics and economic data from São Paulo State only. Furthermore, we realize that the results of the analyses are directly dependent on the parameters included in the analyses and the assumptions and estimates required to conduct the analyses. Nonetheless, the results of the cost–benefit analyses allow for much needed direction for transportation agencies and natural resource management agencies in the implementation and further research and development of mitigation measures aimed at reducing collisions with large mammals and providing safe crossing opportunities for wildlife.

ILLUSTRATION OUTPUT COST–BENEFIT MODEL

We used the carcass removal data from the seven highways (see Table I) to illustrate the outcome of the cost-benefit model and to investigate which highways may reach the thresholds for the four different mitigation measures. We already calculated the average number of road-killed capybaras per kilometer per calendar year for the seven highways, thereby ignoring likely spatial variation in the number of road-killed capybara and associated costs along each highway. To investigate the presence of potential hotspots for capybara-vehicle collisions and associated costs we conducted a spatially explicit cost-benefit analyses at a resolution of 0.1km (highways A through F) and 1.0km (highway G). Since our cost-benefit analyses are based on the number of road-killed capybara and costs per calendar year and the data for highway G only covered part of one calendar year (January through October 2010; see Table I)) we had to apply a correction factor for the number of road-killed capybara on Highway G. We obtained this correction factor from the number of road-killed capybara per month for the other six highways (see earlier in methods). We only conducted the analyses for the seven highways for a discount rate of 3 % and assuming average vehicle repair costs. Note that the threshold values were based on the costs for implementing mitigation measures along a 4-lane road rather than a 2-lane road. Therefore the threshold values are overestimated for highway G.

RESULTS

CARCASS REMOVAL DATA

Of the 26 species or species groups that were present in the carcass removal database for highways A through F capybara was the most frequently recorded mammal species (28%) (Table IV). Most of the mammal species are considered to be of "least concern". Some records did not fully specify the species while other species did not have their conservation status assessed yet by IUCN or there were insufficient data to allow for such an assessment. Maned wolf (near threatened) is killed on the highways in substantial numbers, while giant anteater and oncilla (vulnerable) occur in much lower numbers.

Table IV. The abundance of the mammal species that were present in the carcass removal database for highways A through F and their red list status on an international (IUCN 2012), national (MMA 2008) and state level (SMA 2009). LC = Least Concern, V = Vulnerable, NT = Near threatened, DD = Data deficient, N/A = Not applicable , NY = Not assessed yet. SP = São Paulo State

Species name	Red list status			N	%
	IUCN	Brazil	SP		
Capybara (*Hydrochoerus hydrochaeris*)	LC			462	28.40
Hoary fox (*Pseudalopex vetulus*)	LC			231	14.20
European hare (non-native) (*Lepus europaeus*)	LCn			219	13.46
Armadillo (*Dasypus* sp.)	N/A			142	8.73
Crab-eating fox (*Cerdocyon thous*)	LC			141	8.67
Collared anteater (*Tamandua tetradactyla*)	LC			88	5.41
Maned wolf (*Chrysocyon brachyurus*)	NT	V	V	88	5.41
Gray brocket (*Mazama gouazoubira*)	LC			75	4.61
Rabbit (species not identified)	N/A			28	1.72
White-eared opossum (*Didelphis albiventris*)	LC			26	1.60
South American coati (*Nasua nasua*)	LC			25	1.54
Brazilian porcupine (*Coendou prehensilis*)	LC			23	1.41
Puma (*Puma concolor*)	LC	V	V	20	1.23
Ocelot (*Leopardus pardalis*)	LC	V	V	18	1.11
Monkey (species not identified)	N/A			14	0.86
Neotropical river otter (*Lutra longicaudis*)	NY		NT	5	0.31
Lesser grison (*Galictis cuja*)	LC		DD	4	0.25
Giant anteater (*Myrmecophaga tridactyla*)	V	V	V	3	0.18
Nutria (*Myocastor coypus*)	LC			3	0.18
Crab-eating raccoon (*Procyon cancrivorus*)	LC			3	0.18
Spotted paca (*Agouti paca*)	NY		NT	2	0.12
Marmoset (*Callithrix* sp.)	N/A			2	0.12
Azara´s agouti (*Dasyprocta azarae*)	DD		NT	2	0.12
Peccary (species not identified)	N/A			1	0.06
Oncilla (*Leopardus tigrinus*)	V	V	V	1	0.06
Wild boar (non-native) (*Sus scrofa*)	LC			1	0.06
Total				1,627	100

The number of road-killed capybara for highways A through F showed a seasonal pattern with the highest numbers killed in November through May and lower numbers in June through October (Figure 4). The percentage road-killed capybara in November and December combined was 21.65 % of the yearly total. Thus the correction factor applied to the data for highway G was 1/(1-0.2165)=1.28. The number of road-killed capybara per kilometer per year along the entire length of the seven individual highways varied between 0.07 and 0.72 (Table V).

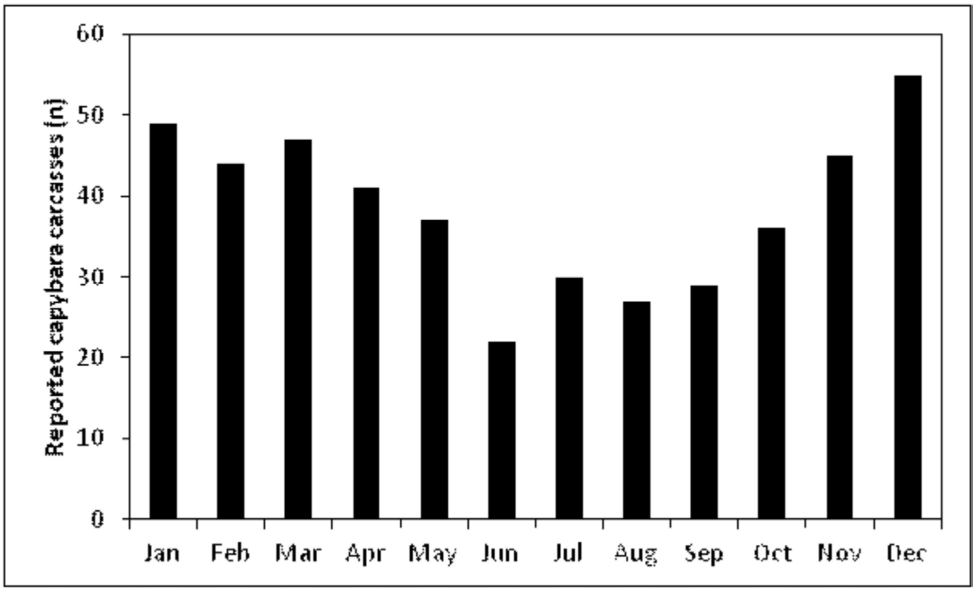

Figure 4. The monthly distribution of road-killed capybara for highways A through F (n=462).

Table V. The number of road-killed capybara per km per year including standard deviation (SD) for the seven highways. * The per year number (2010 only) for highway G was obtained after estimating the number of road-killed capybara for the months with missing data based on the monthly distribution for the other six highways (Figure 4).

Highway	Average/km/yr	
	N	SD
A	0.09	0.04
B	0.39	0.14
C	0.07	0.05
D	0.17	0.05
E	0.17	0.02
F	0.18	0.05
G*	0.72	n/a

COST-BENEFIT ANALYSES FOR CAPYBARA

The minimum amount (in 2012 R$) that a mitigation measure needs to generate in order to reach the break-even point increases with the discount rate (Table VI). Interestingly the break-even points were very similar for the three measures that included differently sized culverts; over a 75 year long period it does not matter very much to put in a slightly larger culvert. These R$-value thresholds were translated into break-even points for capybara–vehicle collisions per kilometer per year (Table VI). If a road section has costs or capybara–vehicle collision numbers that exceed these threshold values, then the benefits of that mitigation measure exceed the costs over a 75-year time period (measured in 2012 R$). For example, if a road section averages 5.4 capybara–vehicle collisions per kilometer per year, a combination of wildlife fencing and any of the three culvert types would be economically attractive because the threshold values (average repair costs, 3 % discount rate) are exceeded. Note that the threshold values presented in Table VI are based on a series of assumptions and estimates and that they should be taken as indicative values rather than exact values.

Table VI. Threshold values for four types and combinations of mitigation measures. The threshold values are expressed in 2012 R$ per kilometer per year as well as the number of capybara-vehicle collisions per kilometer per year for three discount rates (1%, 3% and 7%) and for three estimates for vehicle repair costs (minimum, average, maximum).

Threshold values	**Discount rate**	**Fence**	**Fence, 1.70m diam. culvert, jump-outs**	**Fence, 2.00m diam. culvert, jump-outs**	**Fence, 3x3m box culvert, jump-outs**
R$/km/yr	1 %	R$ 7,221	R$ 9,949	R$ 10,068	R$ 10,234
R$/km/yr	3 %	R$ 8,831	R$ 12,707	R$ 12,917	R$ 13,212
R$/km/yr	7 %	R$ 12,707	R$ 19,616	R$ 20,056	R$ 20,672
Minimum repairs					
capybara/km/yr	1 %	4.88	6.73	6.81	6.92
capybara/km/yr	3 %	5.97	8.59	8.73	8.93
capybara/km/yr	7 %	8.59	13.26	13.56	13.97
Average repairs					
capybara/km/yr	1 %	2.91	4.01	4.06	4.12
capybara/km/yr	3 %	3.56	5.12	5.21	5.33
capybara/km/yr	7 %	5.12	7.91	8.08	8.33
Maximum repairs					
capybara/km/yr	1 %	2.07	2.86	2.89	2.94
capybara/km/yr	3 %	2.54	3.65	3.71	3.79
capybara/km/yr	7 %	3.65	5.63	5.76	5.94

ILLUSTRATION OUTPUT COST–BENEFIT MODEL

The number of average capybara-vehicle collisions for the different highways shown earlier (Table V, ranging from 0.07 for Highway C to 0.72 collisions per km/yr for Highway G), for six of the seven highways in São Paulo State did not reach the threshold values shown in Table VI. However, highway G did reach and exceed these thresholds in some road sections, despite the fact that the thresholds for the mitigation measures were based on the costs for implementation along a 4-lane road (Figure 5). This illustrates that even though the average costs per kilometer per year (see Table V) may not meet the thresholds of the mitigation measures, certain locations on a road section can still exceed these thresholds. For example, the benefits of fencing as a stand-alone mitigation measure exceed the costs on 6.9 % of the 247 kilometer long highway G. Similarly, this percentage was 4.5 % for fencing in combination with any of the three culverts. However, note that the costs are at each 1.0km and that the thresholds need to be exceeded for two consecutive kilometers to have the benefits of a mitigation measure that includes a safe crossing opportunity truly exceed the costs as our cost-benefit analyses include one culvert every 2 kilometers. On the other hand, if the costs associated with capybara-vehicle collisions are higher than the threshold, then these costs can carry over to neighboring road segments that may not have reached the threshold. Interestingly the spatial pattern of the costs associated with capybara-vehicle collisions for Hwy G is very spiky indicating that there are short road segments with a high concentration of capybara-vehicle collisions rather than a more diffuse distribution of these collisions. This also suggests that relatively short sections of fence can keep most of the capybara from getting on the road surface and being exposed to traffic.

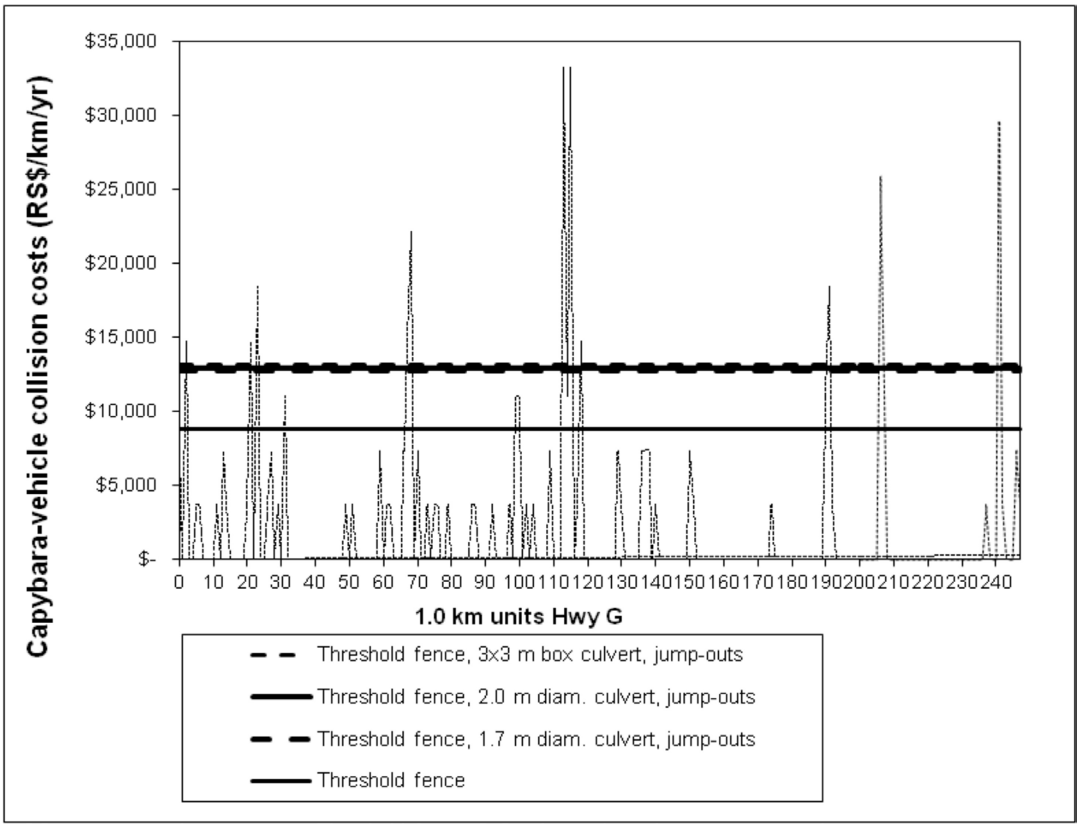

Figure 5. The costs (in 2012 R$) associated with capybara-vehicle collisions along Hwy G (based on data for 2010 only), and the threshold values (at 3% discount rate and average vehicle repair costs) that need to be met in order to have the benefits of the four individual mitigation measures exceed the costs over a 75 year long time period. Note that highway G is a 2-lane road and that the thresholds for the mitigation measures that include culverts are based on the costs for a 4-lane road.

DISCUSSION

CARCASS REMOVAL DATA

There were 26 road-killed mammal species or species groups present in the database for highways A through F, indicative of the biodiversity in this region. Capybara was the most frequently recorded species and also likely the largest and heaviest species. As a consequence capybara is the most likely species to be involved with frequent and substantial vehicle damage and pose a threat to human safety. This justifies focusing on capybara for our cost-benefit analyses. Some of the other road-killed mammal species are considered near threatened (maned wolf) or vulnerable (giant anteater and oncilla) indicating that mitigation measures targeted at reducing wildlife-vehicle collisions could potentially also help species that are considered a conservation priority. Of course the location (habitat) for the mitigation measures, and the type and dimensions of the fencing and crossing structures would have to match the requirements for these other species for there to be a likely conservation benefit. Other studies that reported on roadkill in central and southern Brazil also found capybara frequently hit by traffic, especially in the Atlantic ecoregion (e.g. Cáceres *et al.* 2010). Mammal species that are near threatened, vulnerable or endangered on an international, national, or regional level have also been reported by others. These species include water opossum (*Chironectes minimus*), giant armadillo (*Priodontes maximus*), giant anteater, Azara's agouti, marsh deer (*Blastocerus* dichotomus), pampas deer (*Ozotoceros bezoarticus*), ocelot, puma, jaguar (*Panthera onca*), maned wolf (*Chrysocyon brachyurus*), giant otter (*Pteronura brasiliensis*), and neotropical otter (Coelho *et al.* 2008, Cáceres *et al.* 2010, da Cunha *et al.* 2010, Bager & da Rosa 2011).

The number of road-killed capybara showed a seasonal pattern with the highest numbers killed from November through May and lower numbers from June through October. This pattern is likely related to higher temperatures and precipitation from October through March. This is likely to result in more widespread green vegetation and wet areas allowing capybara to spread out over a greater area. Increased movements during this period could well explain the higher numbers of road-killed capybaras. Conversely, lower temperatures and lower rainfall from May through September causes capybara to concentrate around permanent lakes and wetlands, thereby potentially reducing their movements and exposure to traffic.

Highway G had much a higher density of road-killed capybaras than the other six highways. This may be because highway G is located in the vicinity of two large rivers and the habitat alongside the highway is likely more suitable for capybara. In addition, highway G has only two lanes while the other six highways all had four lanes. This could indicate that capybara are less likely to cross four lane roads compared to two lane roads and that two lane roads, as a consequence, have higher numbers of road-killed capybara. Furthermore, highway G was checked about twice as often for road-killed animals compared to the other highways. The high frequency of road checks along all of the seven highways suggests that many of the road-killed animals are seen by road maintenance personnel. Of course they still have to record the carcasses in order for these observations to end up in the databases. We do not know how consistent road maintenance crews really are in recording road-kill and whether there may be differences between road crews responsible for managing different highways and highway segments. Therefore the roadkill data should be considered minimum numbers which means that the input into our cost-benefit models is conservative.

COST-BENEFIT ANALYSES FOR CAPYBARA

The cost-benefit analyses resulted in threshold values for individual mitigation measures (i.e. fencing and fencing combined with different sized culverts). The threshold values were expressed in 2012 R$ per kilometer per year as well as the number of capybara-vehicle collisions per kilometer per year. If certain roads or road sections exceed these threshold values, then implementing these mitigation measures is economically attractive; the benefits through reducing collisions with capybara exceed the costs associated with the mitigation measures.

We were unable to obtain data on the costs associated with the occasional human injuries and human fatalities, towing, accident attendance and investigation, the cost of disposal of the animal carcass, and passive use costs. This means that our analyses are relatively conservative; the real costs associated with capybara-vehicle collisions are likely to be much higher than our estimates which are based on vehicle repair costs only. For example, the vehicle repair costs associated with ungulate-vehicle collisions in North America were only a fraction of the total costs: 39.6% for deer (*Odocoileus* spp.), 26 % for elk (*Cervus canadensis*), and 18.2% for moose (*Alces alces*) (Huijser *et al.* 2009). Because the weight of capybara overlaps with that of white-tailed deer (*Odocoileus virginianus*) in North America (males 68-141 kg, average 89 kg; females 41-96 kg, average 62 kg) we can expect a somewhat similar risk for human injuries (5% of all collisions with white-tailed deer) and fatalities (0.03% of all collisions with white-tailed deer) (Whitaker 1997, Huijser *et al.* 2009, Foresman 2012). Evidence that capybara-vehicle collisions pose a serious threat to human safety is illustrated by various newspaper articles (Em 2011, OGLOBO 2011, UOL Notícias 2011). In North America the costs associated with human injuries and human fatalities were 56.0% of the total costs for an average white-tailed deer-vehicle collision.

This suggests that a more complete cost estimate for an average capybara-vehicle collision may be about twice as high if we not only include vehicle repair costs but also the costs associated with the occasional human injury and fatality.

For the seven highways we investigated we found that none of these roads had a high enough number of capybara-vehicle collisions to justify the implementation of mitigation measures along the entire road length. However, based on spatially explicit cost-benefit analyses highway G did have several road segments where the costs associated with capybara-vehicle collisions reached and exceeded the threshold values for all four mitigation measures. The costs associated with capybara-vehicle collisions appear to spike in very short road segments, allowing for efficient location of wildlife fencing and culverts. Closer investigation of satellite imagery (Google Earth) revealed that 16 out of the 17 one-kilometer road segments that exceeded at least one of the thresholds for the four mitigation measures were associated with stream crossings or water in the immediate vicinity of the highway. This suggests that while capybara are considered habitat generalists that mitigation measures for capybara-vehicle collisions are best implemented at stream crossings or areas where water or streams are in the immediate vicinity of a road.

Stream crossings require crossing structures because of hydrology alone. Since capybara tend to cross the road at or near stream crossings it seems efficient to implement larger structures wherever streams cross a road. These structures should preferably include dry banks for terrestrial species (e.g. Abra 2012, Clevenger & Huijser 2011). Since the majority of the costs for such a structure are related to hydrology rather than passing capybara, the thresholds for implementing a culvert that is suitable for capybara may be much lower than indicated in our cost-benefit analyses. Alternatively, existing culverts may be modified through providing walkways, either fixed or floating (see Foresman 2004, Kruidering *et al*. 2005, Clevenger & Huijser 2011). Note that the suitability of types of selves or planks for capybara may need to be investigated before implementing them at a large scale. Because of the close association of capybara-vehicle collision locations and stream crossing, the costs for mitigating capybara-vehicle collisions may be mostly with fencing rather than safe crossing opportunities. This analysis illustrates that a one-size fits all approach to use of this benefit-cost tool might miss some opportunities to implement cost-effective collision mitigation. For the case at hand, using the findings as a planning tool can help locate efficient locations for capybara mitigation on this set of highways in São Paulo State. Because the "hot spots" for capybara crossings and collisions are at stream crossings, culvert-related costs for capybara can be minimal and a larger set of collision hot-spots may meet the benefit-cost threshold test. In fact, fencing alone (which is the least expensive mitigation alternative) is likely the only measure specifically related to capybara and most of the costs associated with culverts at stream crossings should not really be attributed to mitigation for capybara.

Cost estimates for the mitigation measures were mostly based on current data from the region. Some cost estimates were based on data from North America, but as explained in the methods these estimates are likely to be overestimating rather than underestimating the costs associated with the implementation of the mitigation measures along highways in Brazil, specifically in São Paulo State. This means that the threshold values we calculated may be too high rather than too low and that the implementation of mitigation measures may be justified with lower numbers of capybara-vehicle collisions than we project in this paper. Interestingly, the threshold values for the three mitigation measures that included differently sized culverts were very similar. Apparently it does not matter very much if a slightly larger culvert is put in if you evaluate the costs over a 75 year long period. Of course the costs associated with collisions with capybara and the mitigation measures are a current estimate and may be subject to change when additional studies are conducted or when more and better data become available. The same is true for the costs (e.g. price of fuel, concrete, and steel) and estimates on the effectiveness of the individual mitigation measures, particularly with regard to reducing collisions with capybara.

CONCLUSION

While mitigation measures are mostly implemented because of concerns for human safety and nature conservation, this paper shows that economics can also justify mitigation measures aimed at reducing wildlife-vehicle collisions and providing safe crossing opportunities. We believe that the cost–benefit model that was applied to the data in this paper can be a valuable decision-support tool for transportation agencies and natural resource management agencies when deciding on the implementation of mitigation measures to reduce wildlife–vehicle collisions. In this case we acquired specific data on the costs associated with capybara-vehicle collisions and mitigation measures targeted at reducing these collisions and providing safe crossing opportunities for capybara. The analysis was made possible by a unique data set showing collisions with 26 different mammal species and species groups. The results suggest that there are road sections in Brazil, and São Paulo State in specific, where the benefits of mitigation measures exceed the costs and where the mitigation measures would help society save money. This is in addition to improving road safety for humans through a reduction in collisions with capybara. Mitigation measures that include safe crossing opportunities for wildlife may not only substantially reduce road mortality, but also allow for wildlife movements across the road. This connectivity is essential to the survival probability of the fragmented populations for some species in some regions. The results of our cost-benefit analyses are quite conservative for various reasons, most notably because the cost estimates for the average capybara-vehicle collision only included the cost of vehicle repair. An important direction for future research would be to develop estimates for human injury and fatality costs, as well as passive use values for some of the vulnerable and/or charismatic species.

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