frontiers | Frontiers in Ecology and Evolution

TYPE Brief Research Report
PUBLISHED 02 October 2025
DOI 10.3389/fevo.2025.1637239

OPEN ACCESS

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RECEIVED 29 May 2025
ACCEPTED 11 September 2025
PUBLISHED 02 October 2025

CITATION
Maharjan R, Young Jr. JH, Ryer K, Rahman MS and Kline RJ (2025)
Assessing the effectiveness of bridge grate and pipe cattle guard designed to mitigate ocelot road mortality on Texas state highway.
Front. Ecol. Evol. 13:1637239.
doi: 10.3389/fevo.2025.1637239

Assessing the effectiveness of bridge grate and pipe cattle guard designed to mitigate ocelot road mortality on Texas state highway

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The mitigated and fenced section of State Highway 100, extending from Laguna Vista to Los Fresnos, includes five wildlife crossing structures and 16 modified cattle guards (also called wildlife guards) installed to mitigate ocelot road mortality. Bridge grate and pipe wildlife guards were deployed at vehicle entries, and we evaluated their effectiveness in preventing meso-carnivores and ungulates from entering the roadway through the fence gaps from April 2020 to 2024. Wildlife guards collectively were >82% effective in repelling ungulate attempts to enter the roadway, while only 16.64% of meso-carnivore attempts were repelled. The pipe wildlife guard (PWG) design repelled 86.79% of ungulates and 18.83% of meso-carnivore attempts to enter the roadway. In comparison, the bridge grate wildlife guard (BGWG) design repelled 81.51% of ungulates and 15.81% of meso-carnivores. Our results indicate that PWG and BGWG effectively prevented ungulates from entering the roadway through fence gaps. Although both PWG and BGWG had low repulsion rates for meso-carnivores, PWG was found to be more effective at preventing meso-carnivores from entering the roadway.

KEYWORDS

ocelot, wildlife crossings, fencing, modified cattle guards, mesocarnivores, mortality, mitigation, wildlife-vehicle collisions

1 Introduction

As of 2021, there are over 6.7 million km of highways in the United States, with over 2 million km in urban areas and over 4.7 million km in rural areas (Federal Highway Administration, 2021). Although roads cover only about 1% of the total land area in the United States, their impact is estimated to affect more than 19% of the country's total land

(Forman, 2000). Moreover, roads pose a serious risk of wildlife-vehicle collisions (WVCs), especially when large mammals gain access to the roadway. Every year, over two million WVCs occur in the United States, involving large mammals, resulting in 200 human deaths and 29,000 injuries (Huijser et al., 2009; Allen et al., 2013). WVCs is estimated at over $8 billion US annually, including vehicle repair costs, carcass removal, human injuries, and accident investigations (Huijser et al., 2009). Efforts to minimize these accidents have led to the development of several mitigation measures, including overpass and underpass wildlife crossing structures (WCSs; Lesbarrères and Fahrig, 2012; Soanes et al., 2024), exclusionary or guidance fencing (Roy et al., 2024; Maharjan et al., 2025), and cattle guards (Belant et al., 1998; Allen et al., 2013; Roy et al., 2024).

The impact of roads is further exacerbated when they intersect protected habitats of endangered wildlife species. State Highway (SH) 100 in south Texas is one of such highways that passes through the Laguna Atascosa National Wildlife Refuge (LANWR), a habitat for endangered ocelots (*Leopardus pardalis*, Jackson et al., 2005). Between 2010 and 2024, three ocelot road mortalities were recorded on SH 100 due to vehicle collisions (Environmental Affairs Division, 2015). To prevent future ocelot road mortality, the Texas Department of Transportation (TxDOT) constructed five wildlife crossing structures (underpasses), 16 modified cattle guards (also referred to as wildlife guards; Allen et al., 2013; Roy et al., 2024), 10 wildlife exits (Sheikh et al., 2023), and continuous fencing over a distance of 11.9 km stretching between Laguna Vista and Los Fresnos (Sheikh et al., 2023).

Overpasses and underpasses allow animals to cross over (i.e., above) safely or under (i.e., below) roadways and structures have been constructed for a wide range of species, including the endangered Florida panther (*Puma concolor*) in Florida (Foster and Humphrey, 1995), red crabs (*Gecarcoidea natalis*) on Christmas Island (Muller and Misso, 2015), bobcats (*Lynx rufus*) in Montana (Huijser et al., 2011), and lemurs (*Lemuroidea*) in the Toamasina province of Madagascar (Mass et al., 2011). With the increase in roads, the demand for mitigation measures is likely to become more prevalent. It may require integrating of these measures for project approvals when roads traverse biologically diverse or protected habitats (Meijer et al., 2018; Maharjan et al., 2024). Additionally, fencing is an effective mitigation measure capable of excluding animals from entering the roadway along the right-of-way (ROW) and guiding them to WCSs. When combined, fencing and WCS have been shown to reduce WVC with large mammals by over 80% in central Arizona (Dodd et al., 2007) and US Highway 93 in Montana (Allen et al., 2013). In urban or developed areas, fence gaps are sometimes necessary to allow vehicles and people to access land. Without WCS along the fenced roadways, animals tend to get funneled towards those gaps, which may allow them to access the roadway (Allen et al., 2013). While vehicle gates can be an alternative solution to prevent animals from accessing the road at fence gaps, it is not always feasible to use gates, especially in areas with high traffic volumes or at road intersections (U.S. Department of Transportation, Federal Highway Administration, 2008). In this scenario, modified cattle guards used by ranchers to handle cattle have proven effective in discouraging animals from using fence gaps to access the ROW (Peterson et al., 2003).

Ranchers have utilized standard cattle guards combined with fencing for decades to prevent cattle from accessing unwanted areas; however, traditional designs are not always safe and effective for heavy emergency vehicles or pedestrians (Allen et al., 2013) and do not account for the jumping or leaping capabilities of wild animals. Therefore, researchers and the state Departments of Transportation have developed alternative designs for wildlife, termed wildlife guards (Allen et al., 2013; Roy et al., 2024). Sebesta et al. (2003) found that the effectiveness of wildlife guards depends on their position and placement. Guards placed over a pit or any raised height using concrete structures can effectively deter wildlife by discouraging them from placing their legs between the grates (Allen, 2011; Sebesta et al., 2003). Peterson et al. (2003) compared three different wildlife guard grate patterns (10.1× 12.7 cm with diagonal cross opening, 10.1× 7.6 cm without diagonal design, and 7.6 × 10.1 cm without diagonal opening) on Florida Key deer (*Odocoileus virginianus clavium*) and found varying repel rates. Allen et al. (2013) indicated that changes in the dimension and design of wildlife guards can create an effective barrier for larger mammalian deer species. While ranchers and farmers have long relied on cattle guards, the widespread adoption of wildlife guards in road ecology remains elusive, rendering research in this area profoundly impactful. We focused on evaluating the effectiveness of two wildlife guard designs (bridge grate and pipe) in repelling meso-carnivores and ungulates found in south Texas. Our evaluation addressed three key research questions: (1) Do wildlife guards effectively deter animals from accessing the right of way (ROW)? We assessed this by determining the percentage of wildlife breaches relative to the number of wildlife interactions or movements near the wildlife guards; (2) Which wildlife guard design is more effective in repelling animals? We compared the repel percentage across two designs; and (3) Which wildlife categories are predominantly deterred by wildlife guards? To ascertain this, we compared the repel percentage among various target species (meso-carnivores: bobcat – *Lynx rufus*, coyote - *Canis latrans*, striped skunk – *Mephitis mephitis*, northern raccoon – *Procyon lotor*, and ungulates: white-tailed deer – *Odocoileus virginianus*, javelina – *Dicotyles tajacu*, wild pig – *Sus scrofa*, nilgai – *Boselaphus tragocamelus*) across the two wildlife guard designs. Although the primary purpose of the guard installation was to prevent ocelots from using the fence gaps, no ocelots were recorded during our study period or at our study location. Therefore, this species was not included in the species categories for analysis.

2 Materials and methods

2.1 Study area

The study was carried out along an 11.9 km section of a four-lane roadway, with each lane approximately 3.5 meter wide, between the towns of Laguna Vista and Los Fresnos in Cameron

County, Texas, USA (Figure 1A). The ROW of this section of the highway has been fenced with an approximate of 1.7 m tall continuous chain-link fence made up of GeoMesh polypropylene fiber (GEO 55), with 16 wildlife guards constructed within the fence gaps. The study area spans grassland and coastal prairie landscapes, managed by LANWR, while private landowners for agriculture and ranchland manage some areas. The area is dominated by the Tamaulipan thorn scrub biotic province but exhibits a distinct mosaic of habitat types at the local scale (Horne et al., 2009; Watson et al., 2019). Within a one-kilometer buffer of SH 100, the dominant land cover types are south Texas wind tidal flats, coastal sea ox-eye daisy flats, and Gulf Coast salty prairie. These habitats are characterized by flat, poorly drained soils, sparse herbaceous vegetation, and minimal canopy cover largely shaped by coastal proximity and saline conditions. Most of the land use around SH100 lies in the semi-arid and subtropical region (Harveson et al., 2004), with an average summer temperature reaching up to 36°C in July-August and an average winter temperature dropping as low as 4°C in January (U.S. Climate Data, 2025). Rainfall typically occurs in spring and fall, averaging about 90 cm annually (U.S. Climate Data, 2025). The area is also home to several endangered wild species, including ocelots and the Northern Aplomado falcon (*Falco femoralis septentrionalis*), along with several other wild mammalian species, such as bobcats, coyotes, northern raccoons, nilgai, white-tailed deer, black-tailed jackrabbit (*Lepus californicus*), nine-banded armadillo (*Dasypus novemcinctus*), javelina, and wild pig.

2.2 Wildlife guard

The wildlife guards installed by TxDOT along the study area aimed to prevent mammalian species from accessing the roadway through fence gaps at the driveway and business entrances within the fenced road corridor. Two wildlife guard designs were used: pipe (PWG, n= 8; Figures 1B, C) and bridge grate (BGWG, n= 8; Figure 1D). PWG was constructed within a metal pipe with a diameter of 8.8 cm each and a spacing of 7.6 cm between adjacent pipes, underlaid with a 15 cm steel I-beam placed in a concrete apron. BGWG featured metal reticuline bars attached to rectangular parallel bearing bars with a spacing of 5.08 cm. Both types of wildlife guards on SH100 measured 4.6 m in width and 6 m in length, positioned above the excavated pit to discourage and prevent wildlife from stepping between the pipes and steel beams (15.24 cm wide), which supported the frame from underneath.

Four PWGs were constructed at the LANWR land access area, and four were installed at fence gaps for private property. Three BGWGs were installed at the LANWR land access area, and five were placed at fence gaps for private property. The wildlife guards were positioned on top of a backfilled depression supported by concrete foundation walls. The depression was approximately 0.5 m deep after installing the grating or pipe. Among eight sites with PWGs, two had chain-link vehicle gates installed during the monitoring phase due to concerns about ocelots using them to access the roadway. However, one site had its gate closed throughout the entire monitoring period, while another experienced irregular access due to the gate opening to private land, which was beyond our control. Since we did not have a sufficient sample size to compare the effect of gates, we decided to remove both WG sites from our study. Therefore, only 14 WGs without the gate were used in our analysis.

2.3 Data collection

Wildlife guards were monitored from April 2020 to April 2024 using two Reconyx (PC900 Hyperfire, USA) Professional Covert Cameras. Two cameras in each 14 WG sites were installed with one passive infrared (PIR) camera deployed to capture motion-triggered images, while the other was active infrared (AIR) triggered camera with an external infrared trip wire system (Seco-Larm E-931S35RRQ13 Enforced Indoor/Outdoor Wall Mounted Photoelectric Beam Sensor, Seco-Larm, USA). AIR camera was used to increase the detection rate of those wildlife using WGs to access the road as well as to minimize the false detections. One camera was positioned at the habitat side of the fenced roadway (a trip-triggered camera capturing three images per trigger), and the other one is motion-triggered camera installed at the fence pole toward the ROW, which captured three photo outputs per trigger. Both cameras were faced toward the entrance of the WG at habitat side, with an average distance of 1 m from the fence, to capture the interactions of wildlife towards the structure (Figure 1B). Those cameras were mounted on a metal post and programmed to take three photographs per trigger, with a one-second interval delay. Cameras were mounted at a height of 30 cm above ground level to enhance the detection probability of medium to large-sized wild animals (ranging from ~14 to 60 cm).

2.4 Data management and statistical analysis

In our analysis, we focused on meso-carnivores (i.e., bobcat, coyote, striped skunk, and northern raccoon) and ungulates (i.e., white-tailed deer, javelina, wild pig, and nilgai). We examined meso-carnivores and ungulates because wildlife guards were primarily installed to prevent ocelots from entering through fence gaps at driveways and refuge roads, and address TxDOT's concerns over collisions with large ungulates. We categorized the behavior of wildlife into three classes based on their actions: class "A"- wildlife breaching the wildlife guards, referred to as breached; class "B"- entering and exiting wildlife guards from the same side without fully breaching it; class "C"- approached the wildlife guards to cross but did not attempt to cross it. Class "A" was considered as breached and used to determine breached %, while classes "B" and "C" were classified as repelled, which was used to establish repelled % (Table 1). Additionally, B and C interactions within a 30-minute period of the same species were counted as single repel to avoid counting the same individual multiple times (O'Brien et al., 2003). We also treated groups traveling together as a single interaction, considering their movements interdependent (Maharjan, 2024). To address the effect of unbalanced sample size between two wildlife guard types, we carried out weighted analysis by adding weights for each WG sites to prevent the overrepresentation group (BGWG) from dominating the inference. The number of target species repelled (interactions B and C) by each wildlife guard category was analyzed using a quasibinomial generalized linear model (GLM) with logit function. This model was selected because the weights used to adjust for the unbalanced sample size were non-integer values and the GLM with quasibinomial family is appropriate in this context as it can handle non-integer weights and proportion outcomes while accounting for potential overdispersion (Zuur et al., 2009). The model included wildlife guard design type (pipe and bridge grate design), species categories, study year (2020-2024) and WG site (Figure 1A). In this analysis, all the interactions with class “A” were coded as 0’s, while class “B” or class “C” were coded as 1’s. The repel interaction between species category and wildlife guard design type (WG types × species category), and study year and species category (Study year × Species category) were also analyzed using full GLM model (Table 2). Overdispersion was tested using Pearson residual divided by residual degrees of freedom (df) to identify outliers in the data and assess how well the model fits the data (Bolker, 2015). The Variance Inflation Factor (VIF) was used to evaluate multicollinearity using the “vif” function from the “car” package in R to check if two or more predictor variables in a model are highly correlated. A pair-wise comparison was conducted using the “emmeans” Tukey test for estimating marginal means to identify significant differences between levels within each factor, with statistical significance tested at a 95% confidence interval ($P<0.05$).

3 Results

Our results illustrate that wildlife guards are effective in preventing wild ungulates ($\bar{x} \pm SE = 82.15 \pm 0.20\%$) from entering the ROW compared to meso-carnivores ($\bar{x} \pm SE = 16.64 \pm 0.09\%$). We also show that PWG was more effective at repelling ungulates (86.79%) and meso-carnivores (18.83%) than BGWG (ungulates 81.51% and meso-carnivores 15.81%). Overall, we documented a total of 10,445 interactions (breached and repelled) across 14 wildlife guards (six PWG and eight BGWGs) for eight wildlife species (four meso-carnivores and four ungulates). The total number of interactions were higher in BGWGs (breached = 774 per BGWG sites, repelled = 183 per BGWG sites) compared to PWGs (breached = 372 per PWG sites, repelled = 94 per PWG sites). Among meso-carnivores, the repelled percentage was less than 36% for each species within this subset for both WG designs, while more than 50% of wildlife interactions for ungulate species were repelled by both designs (Table 1).

During all post-construction monitoring (2020-2024), the mean repelled percentage of target species between the two different WG designs was statistically significant ($P = 0.049$; Table 2). The mean repelled percentage was significantly higher in PWGs (20.12 ± 0.17) compared to BGWGs (19.11 ± 0.10; Figure 2A). Similarly, species categories revealed that the mean repelled percentage were significantly different ($P<0.001$) with a higher repelled percentage of ungulates (82.15 ± 0.20) compared to meso-carnivores (16.64 ± 0.09; Figure 2A). Although the mean repelled percentage for ungulates were much higher in both BGWGs (81.51 ± 0.22) and PWGs (86.79 ± 0.50) compared to meso-carnivores (BGWGs: 15.81 ± 0.11 and PWGs: 18.83 ± 0.17), our statistical analysis showed insignificant interactions between WG type and species category.

Additionally, the repel interaction between species category and study year was found to be statistically significant with a repel percentage for ungulate (ranging from 68.85 ± 0.72 to 91.73 ± 0.25) being significantly higher than meso-carnivores (14.50 ± 0.18 to 19.58 ± 0.26) across all five-study years (Figure 2B). No multicollinearity was observed due to the categorical nature of all variables, and no overdispersion was detected. The repel rate varied among ungulates and meso-carnivores across different study periods ($P<0.001$; Table 2), with higher percentage of repelled individuals noted after 2020 (Figure 2B).

4 Discussion

Comparative studies between the two wildlife guard designs are limited in the published literature, with most focusing only on BGWG (Allen et al., 2013; Peterson et al., 2003) or PWG designs (Belant et al., 1998; Reed et al., 1974). Our findings highlight the importance of considering the specific wildlife guard designs when evaluating their effectiveness. Additionally, our study examined the repel interactions of wildlife guard designs based on species category (ungulates and meso-carnivores). These interactions were found to be statistically insignificant, except for the interaction between study years and species category (Table 2). One of the reasons for the global model being insignificant can be attributed to our limited sample size (n= 14). It might have limited the statistical power and increased the risk of failure for detecting an actual effect in our datasets. In addition, our study did not use a paired or a blocked design; however, the locations were selected to be similar in terms of road characteristics, surrounding land use, and fencing. This allowed for a practical comparison of WG performance while minimizing major environmental variability. Although statistically significant, many of our differences appear practically insignificant. These types of patterns are most common in ecological datasets, where the effects of interactions might not meet the statistically significant threshold due to variability in the nature or limited sample size (Wei et al., 2012).

The *post-hoc* test done for two-way interaction between study years and species category showed the significant difference between meso-carnivores and ungulates across all five-study years, although there was not much significant difference within species category (Figure 2B). Moreover, the repel percentage for each species category increased over time, which might be due to increased human activity near the WG sites, leading to greater avoidance on those sites (Webb et al., 2011). Although our GLM model didn’t provide a statistically significant result between the interactions of

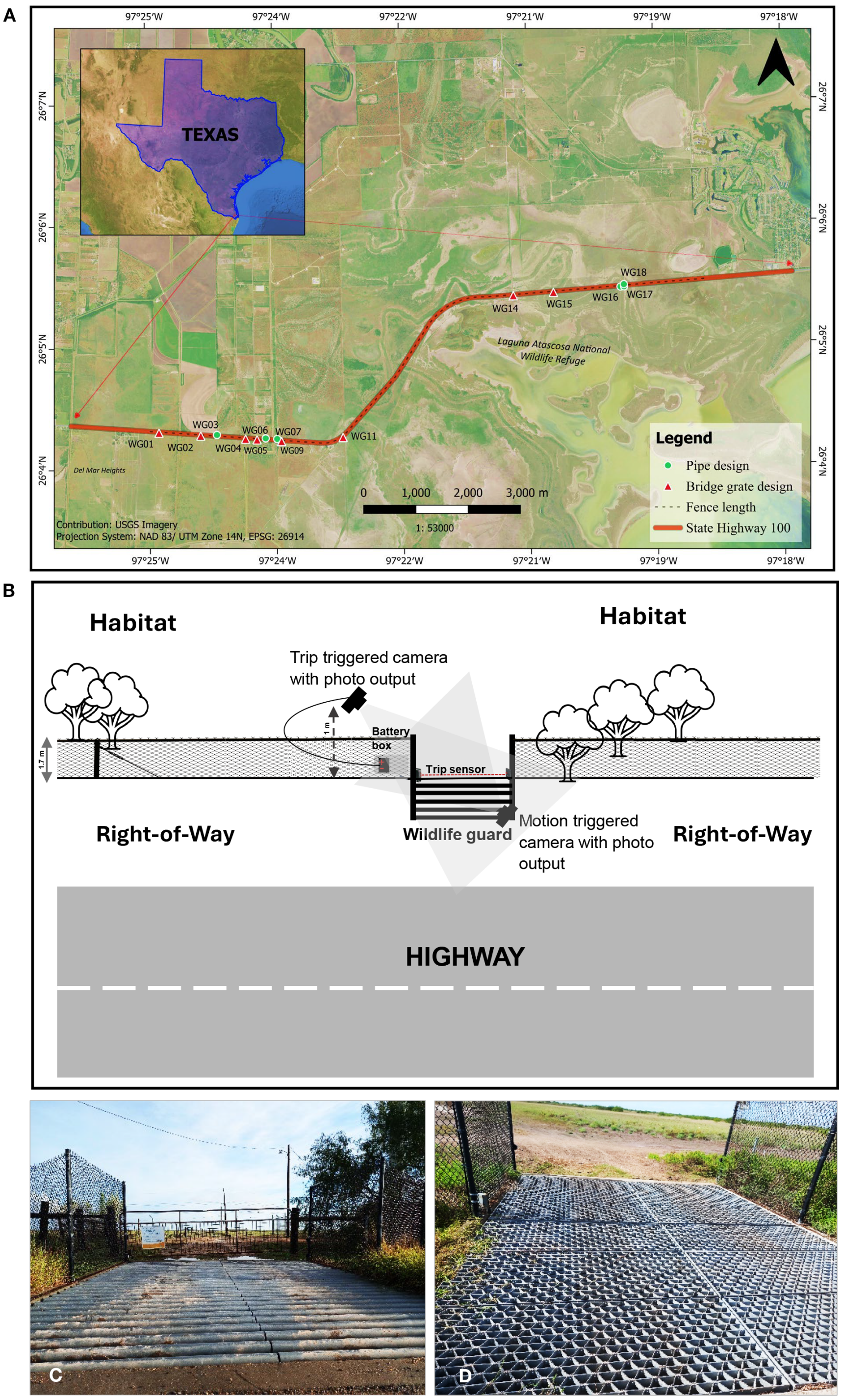

FIGURE 1
(A) Location of wildlife guards along the fenced section of State Highway 100 (SH100). Among the 14 wildlife guards studied, six had pipe design and eight had bridge grate design. **(B)** Illustration of camera trap position at wildlife guard site with one camera positioned at the habitat side of the fenced roadway (a trip-triggered camera), and the other one is motion-triggered camera installed at the right-of-way. Both cameras were faced towards entrance of the wildlife guard and captured three photos per trigger. **(C)** Pipe design wildlife guard installed at six different sites along the section of SH100 and **(D)** bridge grate wildlife guard design installed at eight different sites of the same highway.

10.3389/fevo.2025.1637239

TABLE 1 Frequency of breaches and repelled attempts by meso-carnivores and ungulates categorized based on wildlife guard design types in SH100.

Species	Species category	Approached	Breached	Breached %	Repelled	Repelled %
Pipe						
Coyote	Meso-carnivores	1285	1107	86.15	178	13.85
Striped skunk		383	248	64.75	135	35.25
Bobcat		212	164	77.36	48	22.64
Northern raccoon		860	705	81.98	155	18.02
White-tailed deer	Ungulates	40	6	15	34	85
Nilgai		10	0	0	10	100
Javelina		1	0	0	1	100
Wild pig		2	1	50	1	50
Bridge grating						
Coyote	Meso-carnivores	4742	4124	86.96	618	13.03
Striped skunk		895	632	70.61	263	29.38
Bobcat		157	128	81.52	29	18.47
Northern raccoon		1473	1234	83.77	239	16.22
White-tailed deer	Ungulates	281	39	13.87	242	86.12
Nilgai		64	29	45.31	35	54.68
Javelina		10	3	30	7	70
Wild pig		29	0	0	29	100

TABLE 2 Analysis of deviance table (Type III tests) resulted from the model "glm (All_repel ~ WG Type × Species category × Study year)" with quasibinomial family and logit function.

Variables	LR Chisq	DF	Pr(>Chisq)
WG type	3.875	1	0.049023*
Species category	191.106	1	<2.2e-16***
Study year	73.485	4	4.167e-15***
WG type × Species category	1.875	1	0.170954
WG type × Study year	10.684	4	0.030350*
Species category × Study year	67.633	4	7.170e-14***
WG type × Species category × Study year	18.395	4	0.001033**

WG type includes two design types (pipe design and bridge grate design), species category (meso-carnivores and ungulates), study year (2020 to 2024).
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

WG designs with species category, a higher repel percentage was observed for ungulate in both types of WG designs compared to meso-carnivores (Figure 2A). A similar observation was made regarding the interaction between gate design and species category, although we did not analyze the interactions specifically for WGs with gates in our study. In those case, the repel percentage for both ungulates and meso-carnivores were higher at WG sites with gates compared to those without gates.

The variation in the mean repelled percentage between the two different designs can be attributed to the complexity of their structural design patterns suggesting that the design of WGs may have a significant impact on their effectiveness in repelling target species. The PWG design, featuring a wider opening for foot placement, may have presented challenges for ungulates to walk on the horizontally laid cylindrical steel pipes compared to the bridge grate design, which has grating material positioned diagonally at a 45° angle. Belant et al. (1998) reported results similar to our PWG, where double cattle guards with round bars were more than 85% effective in repelling large ungulates like white-tailed deer. Allen et al. (2013) found the effectiveness of BGWG to be only 60% for white-tailed deer, while our study found it to exceed 85%. Furthermore, Allen et al. (2013) indicated that the design was less effective for carnivores like coyotes (33-55%), whereas our study observed a lower repel rate (coyote-13.03%). Peterson et al. (2003) also tested the effectiveness of a bridge grate design for large ungulates, such as Florida key deer, with findings comparable to ours. However, a study by Reed et al. (1974), which involved flat mill steel rails (1.3 cm wide) installed parallel with 10.2 cm spacing, found the design ineffective for mule deer (*Odocoileus hemionus*), as more than 85% began crossing it after being released, fearing they might be captured again. This finding highlights the importance of design specificity in WGs and suggests that species-specific behavioral response must also be considered to ensure its effectiveness.

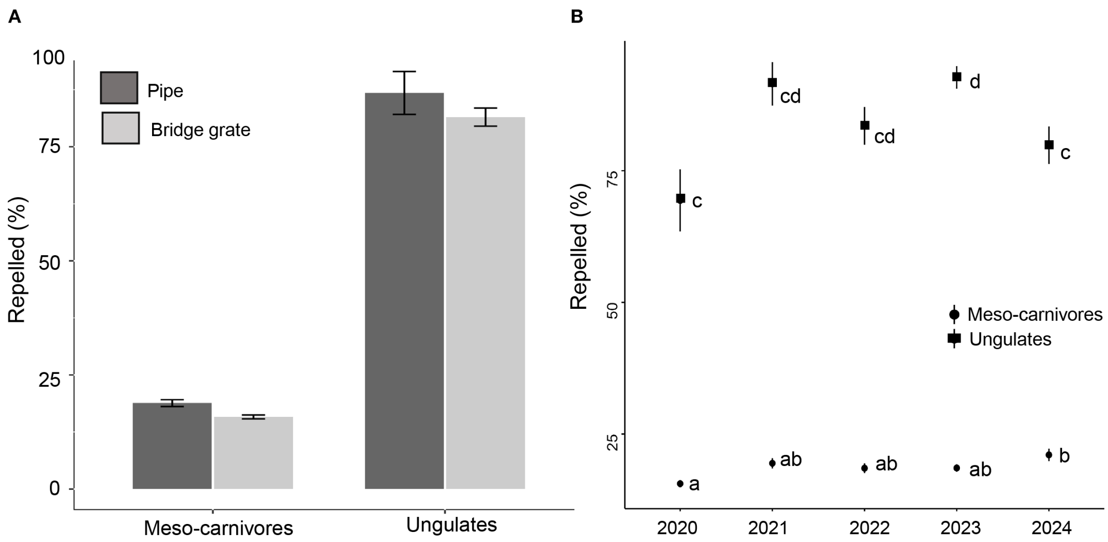

FIGURE 2
Repelled percentage based on species categories, wildlife guard designs, and study year. **(A)** pipe and bridge grate, **(B)** five different study periods of eight species (meso-carnivores: bobcat, coyote, northern raccoon, and striped skunk; ungulates: javelina, white-tailed deer, wild pigs, and nilgai) analyzed at the 14 wildlife guards with pipe (n= 6) and bridge grate design (n= 8). Letters indicate pair-wise comparisons with significant difference ($P < 0.05$) and figure without the letters indicates that the *post-hoc* test was not carried for those interactions due to their statistically insignificant outputs.

The effectiveness of the wildlife guard depends on the morphological and motivational characteristics of the targeted wildlife species. Our research showed that the effectiveness of both wildlife guard designs was lower for meso-carnivores (with paws) than ungulates (with hooves), as soft-footed animals are more agile and can navigate through the guards more easily. Although the PWG design was relatively more effective than the BGWG for meso-carnivores, species such as bobcats and coyotes exhibited hesitancy before crossing, ultimately using the guards to access the roadway. This result suggests the need for additional design features, such as frightening tools like artificial lights (Belant et al., 1998; Koehler et al., 1990), sound (Honda, 2019), and odor (Bíl et al., 2018) to deter wildlife from using the structures. Wildlife guards primarily designed for ungulates should consider the size and agility of the ungulates before installation. For instance, a study conducted by Reed et al. (1974) on Interstate 70 in Colorado found that elk (*Cervus canadensis*) and mule deer accessed the road by crossing a 3.7 m long and 10.2 cm spaced pipe-style wildlife guard by walking, without a recorded instance of them jumping across the guard. In contrast, a field study by Sebesta et al. (2003) along US Highway 1 in Florida found white-tailed deer crossing over a 3.6 m long PWG solely by jumping through it. Our wildlife guard designs were 6 m long, significantly longer than those studied by Reed et al. (1974) and Sebesta et al. (2003), due to concerns that ocelots would be able to jump over them and the necessity to exclude nilgai, a large-bodied ungulate, from the road. We found that hooved animals such as nilgai and javelina were only two ungulate species repelled 100% of the time by PWGs, likely due to the large spacing between the pipes (7.6 cm), while the other two ungulate species (white-tailed deer and wild pig) were not completely repelled. In contrast, BGWGs were less effective, with only a 55% repel for nilgai and a 70% for javelina, while the design repelled 100% of wild pig and about 86% of white-tailed deer. The narrow spacing between the mesh of the bridge grate facilitated these species in walking over the BGWG. However, there was about 14-46% difference in the repellent percentage between nilgai, javelina, white-tailed deer, and wild pigs within BGWG and 15 - 50% in PWG. When designing wildlife guards, we recommend considering the size and agility of the target animals, and the hoof size of ungulates in the area to select an appropriate surface design (e.g., bridge grate, pipe, or other material). Additionally, the length and width of the wildlife guard should also be evaluated based on the size and agility of the species to be excluded. The difference in effectiveness between two WG designs may be attributed to several factors, including overall dimensions of the guard (length and width), species-specific body size (i.e. ungulates vs meso-carnivores), and the structural configuration, particularly the spacing between mesh elements in BGWGs and between pipes in PWGs. These factors likely influence an animal's perception of barrier risk and crossing difficulty, thus affecting their response to the guard.

The low percentage of repel for meso-carnivores using either PWG or BGWG on SH100 suggests that implementing just wildlife guards may not be cost-effective for meso-carnivore targeted road mitigation. During our study, two wildlife guards had vehicle gates added due to high numbers of bobcat crossings, raising concerns about the potential for ocelots to do the same. They were manual chain-link gates made of Geo-mesh polypropylene (GEO 55), installed to fill fence gaps along the exclusion fence. The gate measured approximately 1.7 m in height with a mesh-size of about 5.08 cm, and required a manual operation by push or pull method to open. Although data from these two sites were not included in our analysis, we observed a substantial reduction in bobcat and ungulate crossings following the installation of vehicle gates. Among the two wildlife guards with gates, one opened to private land and had an irregular closing schedule due to high traffic flow, while the other opened to a federal wildlife reserve and was kept closed at all times. Based on our observations within two wildlife guard sites, mesocarnivores, and larger ungulates could breach the WG when the gate was open but faced a significant barrier when it was closed. This suggest that WGs with closed gates could serve as effective deterrents to prevent endangered ocelots from accessing the road through fence gaps. We observed that gates were mostly effective for bobcats and other larger ungulates but not for coyotes and virginia opossums (*Didelphis virginiana*), as these species were very persistent in crossing the gate and utilized the gap beneath it to access the road.

Other forms of modification that may be implemented include electrification. This approach has been explored in several states, including Utah (Cramer and Flower, 2017), Montana (Huijser and Getty, 2023), and Ohio (Seamans and Helon, 2008). They have installed and tested the effectiveness of electrified wildlife guards to repel animals. The electrified guards work by delivering a non-lethal shock to animals that come into contact with it. Despite the installation and maintenance costs, electrified wildlife guards may be effective for other non-hoofed animals. Although there is not much information on the effectiveness of electrified defenses for meso-carnivores compared to ungulates, Siepel et al. (2013) found that black bears were highly deterred from accessing the road by electric mats. Safety considerations are also important, as electrified guards may pose a risk to pedestrians and cyclists. However, some designs produce electric pulses that are not harmful to humans wearing shoes, and option like using a push-button to temporarily stop the electric pulses can allow safe passage for pedestrians or cyclists (Gagnon et al., 2020).

5 Conclusion

We demonstrate that the effectiveness of wildlife guard is affected by its design types with PWG being more effective in repelling ungulates in comparison to BGWG. When designing wildlife guards, we recommend considering the size and agility of the target animals for exclusion, as well as the hoof size of the ungulates in the area; these characteristics can assist in determining an appropriate surface (e.g., bridge grate, pipe, or other design materials) and size for wildlife guard designs. Although wildlife guards in our study were primarily installed to reduce ocelot road mortality by preventing them from accessing the ROW, these structures have been found to be less effective for meso-carnivores. However, combined with vehicle gates the effectiveness of wildlife guard designs could be increased for both meso-carnivores and ungulate species. Further monitoring of additional modifications using diverse deterrent tools such as sound, lasers, and odor may provide valuable insight into improving the effectiveness of wildlife guards at repelling meso-carnivores.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

RM: Validation, Writing – review & editing, Methodology, Formal analysis, Data curation, Software, Writing – original draft, Resources, Conceptualization, Visualization, Investigation. JY: Conceptualization, Visualization, Validation, Writing – review & editing. KR: Visualization, Validation, Writing – review & editing, Conceptualization. MR: Conceptualization, Writing – review & editing, Visualization, Validation. RK: Funding acquisition, Resources, Formal analysis, Project administration, Conceptualization, Writing – review & editing, Supervision, Visualization, Methodology, Software, Data curation, Validation, Investigation.

Funding

The author(s) declare financial support was received for the research and/or publication of this article. This study was supported by funding from the Texas Department of Transportation (grant number 57-3XXIA002) to RK.

Acknowledgments

We would like to thank the Texas Department of Transportation and the United States Fish and Wildlife Services for land access.

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