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Uncovering barriers and paths for ensuring road mitigation to reduce wildlife collisions: Establishing grounds for action

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Abstract

Mitigating wildlife-vehicle collisions (WVC) is crucial for reducing roadkill and preserving biodiversity. This study identifies barriers to WVC mitigation and proposes solutions through an exploratory literature review and formal expert elicitation. We conducted semi-structured interviews with 17 WVC specialists from diverse regions of Brazil, coding 10 key barriers and achieving consensus on 22 solutions. The barriers identified encompass a range of economic, social, political, and technical factors, including road manager type, lack of public policy, and limited societal awareness. The BR-262 highway case study further contextualizes our findings, illustrating how these barriers manifest in real-world scenarios. Co-created strategies with stakeholders emerged as the most effective, with high levels of agreement among specialists. Our results underscore that unaddressed barriers limit the effectiveness of mitigation measures, stressing the need for collaborative approaches that integrate public policy, community engagement, and technical innovation to overcome these challenges.

KEYWORDS

environmental impact mitigation, road ecology, road mitigation, road mortality, stakeholder engagement, wildlife-vehicle collisions

1 | INTRODUCTION

Different sectors impacting biodiversity through factors such as greenhouse gases and urban development face distinct challenges in implementing effective mitigation measures (Bustamante et al., 2014; Rickards et al., 2014; Zhang et al., 2012). Yet, many of these obstacles are shared across fields. Common issues, including bureaucracy, political resistance, and difficulties in engaging stakeholders, often hinder the adoption of environmental strategies (Sanders et al., 2021). Although "barriers" may sometimes refer to physical obstacles in the context of wildlife conservation, here the term is used to describe the social, economic, political, and practical challenges that constrain the effective implementation of mitigation measures.

Among a variety of sectors, infrastructure development, particularly roads, stands out as its expansion exerts growing pressure on ecosystems and threatens biodiversity on multiple levels (Barrientos et al., 2021; Coffin, 2007; Forman et al., 2003). Roads are well-established contributors to the harmful impacts on wildlife populations, including habitat fragmentation and roadkill of wild species (Andrews et al., 2004; Coffin, 2007; Pinto et al., 2020; van der Ree et al., 2015). Mitigating these environmental impacts has become the most commonly adopted strategy to address the extensive damage caused by human infrastructures, providing opportunities to integrate biodiversity conservation into road planning. However, the benefits of mitigation measures are often overlooked or underestimated, exacerbating environmental damages (Juntti et al., 2009). Besides the similar barriers that we see across different fields, there are some general trends related to implementing mitigation measures due to normative responses from decision-makers (Juntti et al., 2009). Decision-makers' disbelief in the benefits of solutions that consider environmental and biodiversity safeguarding, combined with their agenda (when not aligned with conservation), budget limitations, and political fluctuations, often lead them to resist environmental compliance (Haila, 2017).

Moreover, some sectors of society lack perspective on the benefits of mitigation, especially those not directly impacted by the effects of human actions on the environment. This lack of comprehension inhibits possible community pressure in response to environmental consequences. Although the complexity of issues related to wildlife-vehicle collisions (WVC) involves more than just society's expression of concern, several examples have shown that community pressure may in fact contribute to the mobilization of authorities. We highlight, for instance, examples of community pressure that were able to bring attention to the urgency of WVC mitigation to decision-makers. These were successful in acquiring signs, radars, and, in one case, the first overpass in Brazil (Hance, 2023). Decision-makers still hold significant responsibility for conducting the mitigation process, but societal involvement could expedite this process and increase public participation (Grossardt & Bailey, 2018).

Mapping the barriers that affect mitigation processes represents a necessary first step. Once these barriers are described, different stakeholders gain access to information on the main obstacles they would need to overcome to achieve mitigation. It is equally important to map out paths for addressing these barriers. Following new paradigms in conservation also includes developing said solutions with the more significant participation of and input from stakeholders (Cooke et al., 2022; Pereira et al., 2020). Defining barriers is also a critical step for understanding the complex social ties that influence decision-making in a specific field. Common challenges that interfere in mitigation may provide clues to how different sectors of society interact and how to enhance the effectiveness of the mitigation process.

Barrier investigation can be applied to a plethora of different fields that involve environmental impacts. In this context, roads represent a worthwhile opportunity for categorizing critical barriers to contribute to impact mitigation, especially since studies on barriers to WVC mitigation are not systematically addressed in the literature, and in Brazil, few studies specifically discuss these challenges and the obstacles to their implementation. Yet, barriers are freely listed while discussing the assessment of specific mitigation measures, while paths to solutions are rarely mentioned (Andersen & Jang, 2021). In this study, we aim to define possible barriers to implementing mitigation measures and list potential paths to address such barriers. We also include a case study to explore the effects of barriers before and after the implementation of fencing as a mitigation measure.

2 | METHODS

Our methodology for defining barriers to WVC mitigation followed a multi-step framework, adapted from Zhang et al. (2012), that supports structured analysis across different contexts. This framework combines three phases: an initial literature review to establish foundational themes, an expert elicitation process to define and refine context-specific barriers, and a final validation step with anonymous feedback to reach consensus on barrier descriptions. The literature review provided an overview of barriers across fields, serving as a basis for our initial outline and guiding questions used in the expert interviews. The subsequent expert elicitation involved a collaborative protocol in which WVC experts contributed, discussed, and refined barriers, ensuring descriptions were both comprehensive and grounded in practical experience. Finally, we validated these barriers by soliciting feedback from additional specialists, ensuring the reliability and relevance of our findings. Figure 1 illustrates each of these stages within the overall methodology.

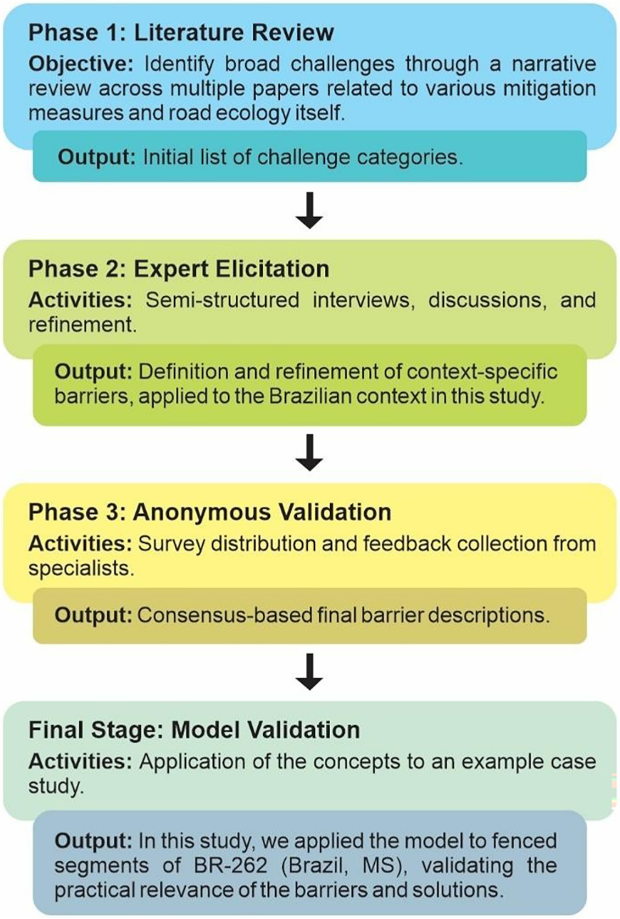

FIGURE 1 Flowchart showing different steps followed in this study.

2.1 | Literature review

The first step within our methodology consisted of conducting a narrative, non-systematic literature review to explore the landscape of barriers to implementing mitigation measures. Narrative reviews allow for a flexible approach, synthesizing broad themes and capturing diverse perspectives without the rigid structure of a systematic review (Baumeister & Leary, 1997). Our goal was not to define closed, fixed categories of barriers but rather to gather insights on how different authors perceive the challenges associated with mitigation. This approach enabled themes and difficulties in implementing mitigation measures to emerge naturally from the literature, providing a foundation for understanding the potential issues we might encounter in our interviews.

Given the limited availability of literature in Brazil on the challenges of implementing mitigation measures related to WVC, we used cases from other fields as the basis for our research. With a combination of the terms "barriers," "mitigation," and "environment," we investigated content that could clarify how barriers are studied in other fields, such as sustainable industry (Gan et al., 2018; Nakagawa et al., 2017; Zhang et al., 2012). We reviewed literature on mitigation measures, including studies that described implementation processes or evaluated different mitigation measures. Our search for peer-reviewed articles was conducted on two platforms: Google Scholar and Web of Science. The search terms applied on both platforms were: (1) collision wildlife roadkill; (2) fencing roadkill wildlife; (3) speed radar wildlife roadkill; (4) wildlife overpass roadkill; (5) wildlife passage roadkill; (6) wildlife warning signs; and (7) wildlife road signs. We did not consider, on either of the platforms, articles that did not focus on the challenges and obstacles associated with implementing mitigation measures for WVC, using the discussion of these barriers as the main selection criteria. The first list of articles included 120 different results that then went through a selection process based on possible barriers mentioned by authors. The process was conducted by two members of Wild Animal Conservation Institute (ICAS) to ensure that all papers addressing challenges and obstacles associated with implementing mitigation measures for WVCs were selected. We then compiled a list of mentions of challenges found throughout the literature, without restricting the analysis to specific sections of the papers. In each article, to identify sentences that mentioned barriers, we defined the following keywords: "mitigation," "mitigation measures," and "problems." We also used the following question as a guide: "What are the difficulties pointed out by the authors in implementing mitigation measures?" Finally, we proceeded by creating barrier categories based on the similarity of the affirmations made by each author. Results from this step were then used to create the general outline of questions in the expert elicitation and to guide the interpretation of the data acquired.

2.2 | Expert elicitation

As a second stage to defining potential barriers to implementing mitigation measures, we conducted an adapted expert elicitation (Hemming et al., 2018; O'Hagan et al., 2006). The protocol is relatively simple to apply and has been tested and shown to yield reliable judgments, with results that have worldwide recognition (Byers et al., 2022). This includes steps such as brainstorming possible actions/solutions, defining and categorizing actions, and validating descriptions collaboratively. Importantly, the protocol incorporates a range of key steps such as open discussions to establish what the problems are, to define and describe actions (here adapted to overcome barriers), and to validate descriptions and concepts defined within the group (here adapted to validation with specialists). As noted above, this methodology has already been adopted to some extent by the conservation community in the context of conservation planning. Remote elicitation has proven to be cost-effective compared to face-to-face methods, as demonstrated by the collaborative virtual efforts for *Scotland's beaver strategy 2022–2045* (IUCN/CPSG, 2022) and the *Workshop for the Development of the Conservation Action Plan for the Saíra-apunhalada* (Instituto Marcos Daniel, 2021), which highlight reduced logistical costs and expanded accessibility for participants in conservation planning efforts.

2.2.1 | Semi-structured interviews

Following the expert elicitation methodology, we developed an interview script (Supporting Information S1) for our first stage in defining barriers to mitigation implementation. We decided to conduct qualitative semi-structured interviews (Newing & Eagle, 2011), following a general outline of questions and topics to be covered while maintaining the flexibility to inquire further and explore responses in greater depth. This approach facilitated a fluid exchange of information, which could be later categorized and analyzed for data classification purposes. Each interview was based on the specialist's perception of (1) what the barriers to implementing mitigation measures are; (2) how specialists would group the cited barriers; and (3) paths to overcome such barriers.

To identify specialists for the interviews, we employed a combined method using a list of authorities in the field of mitigation measures that could be interviewed, along with snowball sampling (Goodman, 1961). In this process, interviewees were asked to name another potential specialist, who would then suggest another name, and so forth, creating a chain of referrals to expand the pool of potential interviewees. We only interviewed specialists that had experience in Brazil. We also prioritized a diversity of participants from different regions, biomes, and states to obtain distinct points of view from throughout the country.

2.2.2 | Codification and validation of quantitative categories

As the last stage for independent validation, we conducted an online survey (Supporting Information S2) verifying if additional specialists agreed in relation to the existence of the barrier. Specialists were also asked to confirm if the barrier description was adequate, and finally to assign a relative level of importance to each barrier ranging from 1 to 5 (1 as the lowest value and 5 as the highest). Next, the level of importance was converted to a relative importance index that corresponds to the average value obtained from all specialists. We included the list of proposed solutions and asked specialists to assign a level of agreement to each solution, using a scale from 1 to 5, where 1 represents "Strongly disagree" and 5 represents "Strongly agree." To facilitate the interpretation of responses, we categorized solutions based on the level of consensus among specialists: "High" indicates solutions where over 75% of responses show strong agreement, "Moderate" captures solutions with a more balanced distribution between "Agree" and "Neither Agree nor Disagree" and "Low" represents solutions with less than 50% agreement and relatively higher levels of neutrality or disagreement. This categorization aims to clarify the relative consensus or divergence in the perceived effectiveness and feasibility of each solution among specialists, providing insight into priority areas and potential challenges.

We submitted an online survey to the Brazilian Network of Transportation Ecology Specialists (REET Brasil), an established association that brings together specialists in transportation ecology, particularly in the application of biodiversity monitoring and impact mitigation. The target population consisted of 174 Road Ecology Specialists, all members of REET Brasil, with demonstrated expertise in WVC monitoring and mitigation.

The survey remained open for free validation for 15 days, during which we sent multiple invitations every 5 days via a WhatsApp group dedicated to technical discussions on road ecology to maximize participation. In the end, we received nine contributions, representing a 5% response rate. While this percentage may appear low in broader survey research, it is consistent with response rates commonly observed in expert-based surveys, particularly in highly specialized fields with a limited pool of respondents (Hsu & Sandford, 2007).

Moreover, according to an official statement from REET Brasil, previous surveys conducted within the network have yielded similar response rates, reinforcing the representativeness of our sample despite its absolute size. This is particularly relevant in Brazil, where the number of experts in road ecology remains low and concentrated in specific institutions and regions.

Unlike the first round of responses, contributions received during the validation period were anonymous and included specialists from various parts of Brazil, as long as they matched the main inclusion criterion: being a member of the REET Brasil network. We did not exclude individuals who may have participated in the initial round, as long as they continued to meet this criterion. After data coding, the barriers differed from those originally proposed, incorporating the perspectives of the specialists to shape the final set of barriers. Therefore, we do not believe that input from respondents who participated in both rounds biased the validation process. The study was approved by the Brazilian National Commission for Research Ethics (CAAE n° 53975221.2.0000.5380). All participants provided their informed consent to participate.

2.3 | Case study

Intending to exemplify how barriers may affect the process of accomplishing the implementation of mitigation measures, we used a case study. We chose a case where the process for implementing a mitigation measure had been fully undertaken. The selected case study consists of fence segments as a mitigation measure on a road famous for its high rates of WVCs, BR-262, located in Mato Grosso do Sul, Brazil. This road has an extensive database of systematically collected WVC data; therefore, we also concluded that it would be possible to evaluate which barriers affected the success of the implementation of mitigation measures to prevent WVCs. In this case study, we looked at both barriers interfering in the process of mitigation measure implementation and its success. We had data available based on systematic monitoring, between 2011 and 2021 (with some gaps, totaling 212 periodic surveys in 6 years—weekly or fortnightly), including the pre- and post-fence implementation period that could be used in a Before-After-Control-Impact (BACI) study to understand whether the fences had an impact on reducing WVCs. Our data, provided by ICAS or by Brazil's National Department of Transportation Infrastructure (DNIT), includes 9120 records of wild vertebrate roadkill in a segment of 278.3 km of BR-262, resulting in a rate of 5.5 roadkill/km/year, with mammals representing 47%, reptiles 31%, birds 20%, and amphibians 2%. Caimans (*Caiman yacare*) represent 17.9% of records, followed by nine-banded-armadillo (*Dasypus novemcinctus*—8.3%), crab-eating-fox (*Cerdocyon thous*—8.0%), six-banded-armadillo (*Euphractus sexcinctus*—7.7%), and capybaras (*Hydrochoerus hydrochaeris*—5.5%).

2.3.1 | BR-262 road and fencing

The BR-262 highway is a national road, managed by DNIT. The road crosses the state of Mato Grosso do Sul from east to west, through natural areas of the Cerrado (native savanna) and Pantanal (native wetlands) biomes. This road is well-known as the "death road" due to high levels of wildlife loss through WVC every year (Ascensão et al., 2019, 2021; De Souza et al., 2015). The species most frequently involved in WVCs include the capybara (*Hydrochoerus hydrochaeris*), crab-eating fox (*Cerdocyon thous*), and caiman (*Caiman yacare*), while previous surveys also highlighted high incidences among other mammals such as *Euphractus sexcinctus* and *Myrmecophaga tridactyla* (Cáceres et al., 2012; Ferreguetti et al., 2020). Also, it is one of the few examples of roads that had mitigation measures implemented in Central Brazil to reduce WVC. The road is also among the most dangerous in the state in terms of human fatalities, with official records from the federal highway police reporting 161 fatal accidents between 2017 and 2019; of these, six involved wildlife, resulting in eight human fatalities. In June 2019, between the municipalities of Anastácio and Corumbá, in areas of Cerrado and Pantanal, fences were installed at the extremities of pre-existing bridges in BR-262, with the intention of preventing animals from accessing the road and guiding animals to cross under the road. Five fences were installed in isolated bridges (100 m at each extremity), resulting in a short length (on average 262.6 m between fence extremities), and two fences were installed connecting bridges, resulting in longer lengths (3.3 and 3.9 km). The extension of fences only represented 3% (8.5 km) of the road segment considered for intervention (278.3 km). This action originated from an environmental program established by IBAMA, the Brazilian Institute of the Environment and Renewable Natural Resources, which issues environmental licenses and oversees compliance with prior conditions imposed on the infrastructure agency, DNIT. The fencing measure was implemented as part of this program through a directive from Brazil's Public Ministry, with significant support from a popular motion. Understanding this implementation process, we initially focused on evaluating the barriers involved in enacting the mitigation measure. After evaluating the effectiveness of the mitigation measure (Supporting Information S3), we identified the key barriers that significantly impacted its success. Each barrier was assessed considering (1) the historical context for implementing the measure, (2) the estimated effectiveness of the measure, and (3) its current status. This analysis aimed to reveal that while these barriers were not fully eliminated, the implementation process allowed for partial mitigation of some barriers, ensuring the measure's adoption even if not achieving full effectiveness.

3 | RESULTS

3.1 | Barriers to implementing mitigation measures

3.1.1 | Literature review

From the initial set of 120 articles, we selected a total of 103 peer-reviewed articles related specifically to mitigation measures for WVCs (Google Scholar: 45; Web of Science: 58). The mitigation measures identified in the search included warning signs, overpasses, wildlife passages/crossings, speed radars, and fencing. Among the selected articles, 73 (70.87%) mentioned challenges in implementing mitigation measures; however, these were not systematically classified as "barriers" by the authors. We documented each instance where challenges to implementing mitigation were mentioned across the articles, resulting in a total of 120 mentions. These mentions may include repeated references to the same types of challenges across different sources.

We grouped the mentions into six main categories to facilitate the identification of common challenges and provide an initial overview of general barriers. This categorization served as a foundational step, which would later be expanded upon through expert elicitation to capture a more detailed view of barriers specific to a Brazilian context. The six categories identified were: (1) barriers related to cost or economics (no. of mentions = 40); (2) barriers related to ecological or biological aspects of biodiversity (no. of mentions = 32); (3) barriers related to lack of knowledge of different parts of the mitigation process, including measure efficiency (no. = 21); (4) barriers related to technical aspects (no. = 11); (5) barriers related to political and institutional aspects (no. = 9); and (6) barriers related to road user behavior (no. = 7). The classification from the literature served as a basis for interpreting the results obtained during the round of expert elicitation.

3.1.2 | Expert elicitation

We conducted semi-structured interviews with a total of eight specialists in the first round, including five university researchers, one environment agency specialist, and two consulting specialists. During the validation stage, we received nine anonymous contributions from REET Brasil, an organization of 310 members, including academics, environmental consultants, public agency professionals, entrepreneurs, and non-profit representatives from across all of Brazil's regions. The interviews yielded approximately 5 h of recorded content, producing an initial list of 27 barriers, which were grouped by similarity into 10 categories. The validation stage and co-production feedback confirmed these final 10 barrier categories (Table 1).

We incorporated changes in the description of barriers, along with the insertion of additional information, in a few cases. The expertise of specialists also provided general considerations related to each barrier, allowing us to further detail our descriptions. Thus, the expert elicitation process followed an iterative co-production approach, in which the descriptions and groupings of barriers were continuously refined based on expert input. This co-refinement ensured that the final barrier descriptions effectively represented the experts' insights in a unified way, capturing shared nuances.

Regarding the level of importance of each barrier, the top three were: B1 (road managers; relative importance: 4.77); B2 (lack of public policies; relative importance: 4.77); and B3 (financial cost–benefit ratio; relative importance: 4.22). The values of importance did not differ greatly between barriers; the lowest value was calculated for the last three barriers: B8 (legal means), B9 (research), and B10 (innovation constraints) (relative importance: 3.44) (Figure 2).

Finally, we obtained a total of 22 proposed paths to implementing mitigation measures, suggested by different specialists. We retained all proposed paths for the final evaluation phase to assess the level of agreement among specialists regarding each path for overcoming barriers to mitigation. The results showed a significant amount of agreement regarding solutions to implementing mitigation measures (Figure 3). The top-ranked solution, agreed upon unanimously by specialists, was "Sector Co-Production," followed by "Mitigation Included in Privatization." The solutions with the lowest level of agreement were "Gov. Research Funding" and "Legal Solutions."

Each solution reflects a specific area where specialists identified potential to address barriers. Solutions with high agreement, such as "Sector Co-Production," "Mitigation Included in Privatization," and "Tech Innovation," underscore the importance of cross-sector collaboration and early integration of mitigation strategies within road management processes. Solutions classified as moderate, such as "Social Value Development" and "Regulatory Consistency," emphasize supportive policies and cultural changes that may facilitate gradual, long-term progress. Conversely, "Gov. Research Funding" and "Legal Solutions" received lower levels of agreement, likely due to the complexities surrounding public funding and legal frameworks, which can be time-consuming and challenging to navigate (Table 2).

TABLE 1 Full report of the barriers related to the implementation of mitigation measures.

Code	Barrier description
B1	*Road Manager Type*: Delays in mitigation efforts depending on whether the road is managed publicly or privately. Public managers often face bureaucratic hurdles, while private managers may delay compliance with environmental requirements.
B2	*Lack of Public Policies*: Absence of political will and low awareness among decision-makers, leading to insufficient planning that does not view mitigation as a beneficial long-term investment.
B3	*Financial Constraints*: Challenges related to the costs of implementing and maintaining mitigation measures, including the difficulty of recognizing these costs as necessary investments rather than expenses.
B4	*Institutional and Political Obstacles*: Complications arising from the structure of institutions responsible for mitigation, which often do not prioritize such measures early in the project lifecycle.
B5	*Social Perception*: Limited societal recognition of the importance of mitigation measures, and a lack of established culture or widespread support for their implementation.
B6	*Lack of Expertise*: Deficiency in knowledge and preparedness among government and private sector analysts when it comes to environmental licensing and implementing mitigation measures effectively.
B7	*Communication Issues*: Ineffective communication of the benefits and importance of mitigation measures, resulting in misunderstandings and delays. Clear, accessible, and inclusive communication is essential.
B8	*Legal and Bureaucratic Barriers*: Legal procedures and bureaucratic processes that slow down mitigation efforts, demanding significant organization and effort from stakeholders.
B9	*Research Limitations*: Challenges related to the availability, quality, and communication of scientific research, including the type of data collected, sample sizes, and how results are conveyed to decision-makers.
B10	*Technical and Innovation Constraints*: Difficulties in developing and adapting new mitigation solutions that fit local ecological and environmental contexts, as well as challenges in approving new measures after initial project approvals.

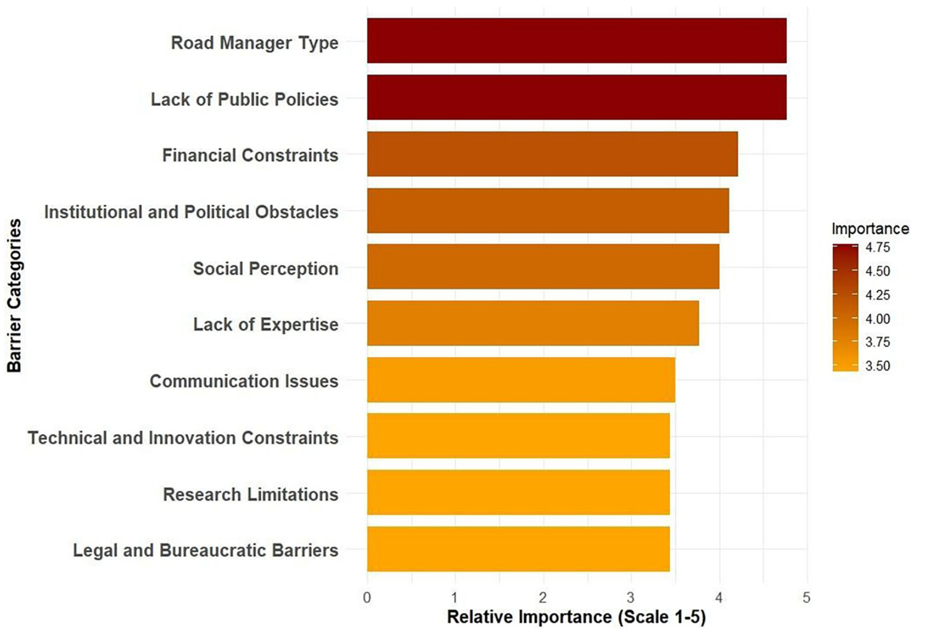

FIGURE 2 Barrier categories and their relative importance on a scale from 1 to 5.

3.2 | Case study results: Application of the concept of barriers with the implementation of road fencing at a federal level

After evaluating the case study, we were able to determine that the following barriers were addressed at some level to accomplish the implementation of fences B1: Road Manager Type, B2: Lack of Public Policies, B4: Institutional and Political Obstacles, B5: Social Perception, and B9: Research Limitations. The evaluation of the success of this mitigation measure revealed that only long fences were effective at reducing fatalities related to one species (*Caiman yacare*) (Yogui in preparation); although

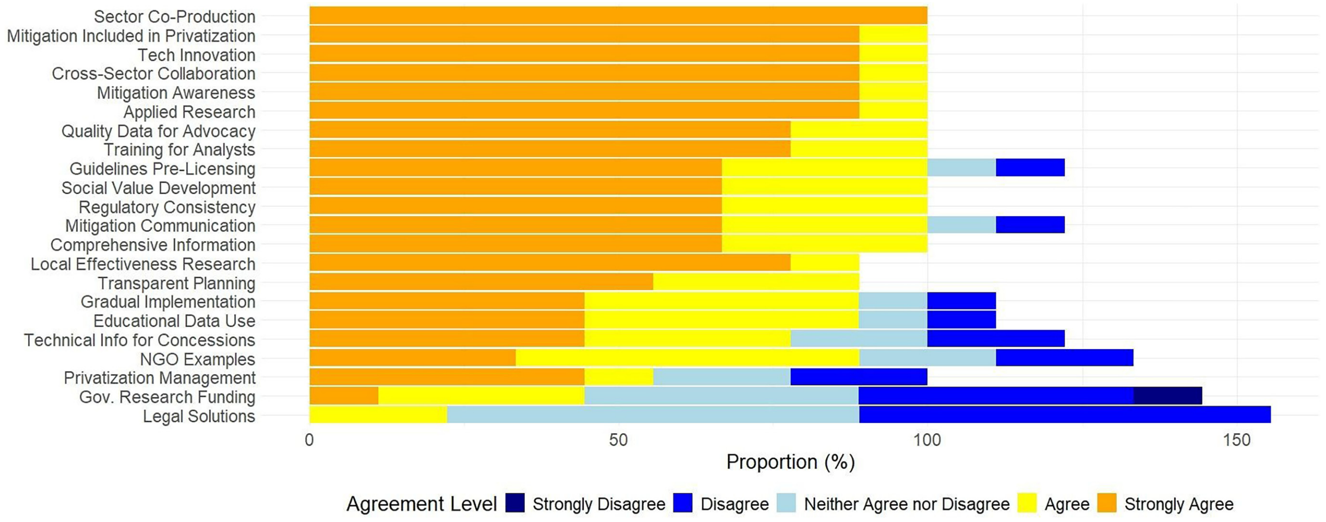

FIGURE 3 Stakeholder agreement levels on suggested paths for mitigating wildlife-vehicle collisions. Each bar shows the proportion of responses across five levels of agreement: Strongly Disagree, Disagree, Neither Agree nor Disagree, Agree, and Strongly Agree. The percentage values can exceed 100% because each level of agreement is plotted individually, allowing responses for each agreement level to accumulate across categories.

they were not specifically built for this species, they were built for medium/large animals in general. Fences do not show an effect in the mortality of abundant mammals, such as the crab-eating fox (*Cerdocyon thous*) or capybara (*Hydrochoerus hydrochaeris*), nor endangered species. Our results suggest that the same barrier model applies in this case because we identified barriers consistent with those in our study and were able to evaluate how the implementation process helped overcome some of them, even if only partially. We highlight the following factors contributing to this outcome: fences were installed in response to community pressure (B5 societal perception influence); some segments were too short (100 m each side), reflecting limited specialist input (B9); longer fence segments were prioritized for caiman collision hotspots, influenced by institutional bureaucracy (B4); fences lacked robustness and maintenance, resulting in holes, some created by the local community for stream access (B1 and B2), indicating public management limitations and the absence of supportive public policies.

We identified, through the comparison of case study information and the definition of the barriers, that B2: public policies, B5: value of mitigation, and B9: lack of expertise were only partially addressed when the fences were installed. We also identified that if B3 and B6 had received attention during the process, the outcomes would have been more efficient. For this specific case study, other barriers were not identified (Table 3).

4 | DISCUSSION

4.1 | Barriers to implementing mitigation measures

Our findings contribute a structured view of the challenges to WVC mitigation in Brazil, complementing existing road ecology research that explores these challenges globally but lacks a systematic focus on these issues. However, the obstacles we identified, such as political dynamics, costs, lack of social relevance, and research-related issues, have specific nuances that contribute directly to the field of road ecology. Compared to fields like greenhouse gas emissions mitigation and green infrastructure adoption (Bustamante et al., 2014; Gan et al., 2018; Zhang et al., 2012), the barriers to mitigating WVCs demand cross-sectoral integration—including areas such as budgeting, infrastructure and road engineering, management, environmental licensing, economics, politics, and social engagement—that extend well beyond road infrastructure alone. Our findings suggest that road ecology can benefit from a collaborative governance approach, where integrated planning and local adaptation of mitigation measures are critical to success. Additionally, by establishing these barriers as central to road ecology, we provide a foundation for interventions that are not only reactive but also preventive, potentially informing public policies and stakeholder engagement that reinforce the adoption and monitoring of effective mitigation measures.

TABLE 2 This table summarizes proposed solutions for implementing wildlife-vehicle collision mitigation measures, categorized by the level of agreement among specialists into "High," "Moderate," and "Low" agreement categories.

Solution	Agreement level	Potential success factors	Challenges/limitations
Sector Co-Production: Collaborative efforts across sectors	High	Builds on multi-sector expertise, enhancing impact	Requires strong coordination across sectors
Mitigation Included in Privatization: Integrate mitigation in road privatization	High	Early-stage planning, integration into private projects	Depends on private sector compliance
Tech Innovation: Local tech solutions for mitigation	High	Localized tech solutions provide adaptability	Requires research/ development investment and local tech capacity
Cross-Sector Collaboration: Engage engineers and policymakers	High	Leverages expertise from multiple fields	Coordination challenges with conflicting objectives
Mitigation Awareness: Raise awareness of mitigation importance	High	Promotes public and policy support for initiatives	Gradual impact; requires sustained awareness efforts
Applied Research: Invest in research for practical solutions	High	Evidence-based approach for practical solutions	Funding and time constraints may limit applicability
Quality Data for Advocacy: Use solid data to influence policymakers	High	Data strengthens advocacy efforts with decision-makers	Effectiveness depends on receptiveness of policymakers
Training for Analysts: Provide training for workers and analysts	High	Improves informed decision-making, reducing delays	Requires training resources; potential low participation
Guidelines Pre-Licensing: Set guidelines before road licensing	High	Ensures early-stage inclusion in project planning	Adds project costs; needs regulatory support
Social Value Development: Build societal values with examples	Moderate	Establishes cultural support for long-term measures	Impact is gradual and difficult to quantify
Regulatory Consistency: Consistent enforcement by regulatory bodies	Moderate	Enforces compliance through strong oversight	Can be influenced by political or institutional biases
Mitigation Communication: Clear communication on mitigation benefits	Moderate	Facilitates public and stakeholder understanding	Requires clear messaging and frequent updates
Comprehensive Information: Provide detailed guidance on implementation	Moderate	Offers thorough guidance for mitigation implementation	Access and dissemination challenges
Local Effectiveness Research: Research local mitigation effectiveness	Moderate	Tailors solutions to regional needs	Limited by funding for long-term studies
Transparent Planning: Plan improvements transparently	Moderate	Builds accountability and transparency	May meet resistance due to financial disclosure
Gradual Implementation: Adopt a gradual approach to mitigation	Moderate	Phased approach eases adoption	Less impactful in the short term
Educational Data Use: Use scientific data in public education	Moderate	Raises public awareness through data	Impact may be gradual; outreach needed
Technical Info for Concessions: Access to technical data for concessions	Moderate	Enables informed planning during concessions	Access issues; reliant on data-sharing platforms
Non-Governmental Organization (NGO) Examples: Show NGO and community mitigation efforts	Moderate	Shows community and NGO-driven mitigation models	May lack visibility without widespread support
Privatization Management: Use privatization to improve management	Low	Efficient management through private sector resources	Reduced public oversight, regulatory dependency
	Low	Advances knowledge before licensing	

(Continues)

TABLE 2 (Continued)

Solution	Agreement level	Potential success factors	Challenges/limitations
Gov. Research Funding: Fund research before licensing			Public funding challenges and possible delays
Legal Solutions: Address issues with legal frameworks	Low	Provides enforceable solutions for mitigation	Legal processes are slow; requires advocacy

TABLE 3 Barriers analyzed through the optic of the case study.

Code	Barrier name	Case study: Fenced segments BR-262
B1	Road Manager Type	This barrier was partially overcome through the process.
B2	Lack of Public Policies	This barrier still lacks political will for the implementation of new fencing segments.
B3	Financial Constraints	No, fences were not effectively implemented.
B4	Institutional and Political Obstacles	This barrier still lacks political will for the implementation of new fencing segments.
B5	Social Perception	The attention received through the media increased the value of the mitigation.
B6	Lack of Expertise	No, fences were not installed according to the best technical parameters.
B7	Communication Issues	Does not apply.
B8	Legal and Bureaucratic Barriers	Does not apply.
B9	Research Limitations	Partially, research was considered but not to its full potential.
B10	Technical and Innovation Constraints	Does not apply.

When analyzing the specificity of each barrier, we can draw a few conclusions. Slowness is the main consequence of the B1: road managers. Quite often, when considered by decision-makers, technical evidence does not become part of the final project. The resistance against incorporating mitigation measures into structured planning leads to inertia from decision-makers, or even poorly applied mitigation. In the case of private managers, mitigation measures, when not a contractual obligation, tend to be secondary investments, limited by budget or compliance mechanisms. The reasons for slowness may fit into the reasons for the low number of decisions made based on evidence, especially regarding the environmental sector (Juntti et al., 2009). In this case, norms, political dynamics, and power play an important role in defining the decisions made by public and private institutions. It is also important to point out that political decisions tend to be based on old established models, taking into consideration factors such as reputation and peer pressure (Rickards et al., 2014). When looking at the private sector, further consideration indicates that social participation is also key for ensuring the compliance of constraints established by environmental agencies (Talukdar & Meisner, 2001). Moreover, the potential of a private sector with compliance enforced through licensing constraints has evidence in other fields (Andersson et al., 2018).

When analyzing the specificity of each barrier, we observe that “slowness” primarily stems from road managers' reluctance to incorporate mitigation structures into planning, construction, and operational phases, especially without regulatory enforcement. State-operated road managers often resist these structures, as they complicate construction plans and demand integration from the early planning stages through to ongoing maintenance, requiring additional studies, resources, and institutional approvals. This adds to the bureaucratic processes within their own institutions, amplifying the “slowness” factor. Conversely, private operators tend to deprioritize mitigation efforts due to financial implications, viewing them as secondary investments unless compliance is mandated. Evidence from other sectors suggests that effective enforcement through licensing requirements can improve compliance in the private sector (Andersson et al., 2018). This resistance, whether due to operational complexities or cost considerations, frequently results in delayed or poorly implemented mitigation. Additionally, political and social dynamics—such as adherence to established norms, political pressures, and reputational concerns—often sway decision-making, with political entities generally favoring traditional practices over innovative, evidence-based approaches to mitigation (Juntti et al., 2009; Rickards et al., 2014). In both public and private contexts, community engagement and strong enforcement of environmental constraints play critical roles, as social factors and media pressures can influence the process's agility and transparency (Talukdar & Meisner, 2001).

We understand that B2: public policies and B4: political dynamics are commonly related to a lack of public policies linked to WVC and compliance with the environmental licensing process, as well as consideration of measures in the early stages of licensing. Impact assessment within the Brazilian legal structure has had several pitfalls historically and includes weak points that could be improved upon, despite being considered the only opportunity for ensuring compliance with constraints in the case of large infrastructures (Duarte et al., 2017). Understanding the need for early inclusion of mitigation measures in the process is critical to ensuring its proper installment (Andersen & Jang, 2021). We believe that efficient compliance together with advances in public policies related to WVC is a key component to overcoming these barriers.

Cost is possibly a complex barrier (B3) that overlaps with society's perceived value of mitigation (B5), as well as poor communication efforts to inform the need to invest in mitigation measures (B7). There is literature that predicts return on investment in the short–medium term, considering multiple costs including the fencing cost of areas (Ascensão et al., 2021). Despite the multiple costs to road managers with the general aspects of road maintenance, there are further financial costs to society that include vehicle repairs, psychological costs, insurance, and medical expenses, which can be significant (Abra et al., 2019). Also, other parameters should be considered while analyzing the financial cost–benefit ratio of mitigation. There is little consideration for the intrinsic value of wildlife, not to mention human life. Fatalities involving wildlife species represent a threat to human security. Moreover, there is no estimate of the cost for ecosystem services lost with this impact on wildlife populations. The awareness of these costs, financially and beyond, could prevent the use of mitigation measures with low impact in WVC, such as road signs.

Another important and frequently debated barrier was the lack of expertise (B6) among some environment agency analysts in relation to mitigation measures. Most agree that these analysts are generally well prepared for the licensing process itself. However, WVCs require specialized knowledge—such as road ecology, engineering, and social sciences—that is essential for effective mitigation. In this context, including road ecology specialists at the early planning stages and consulting with wildlife biologists during option development are both critical to addressing these knowledge gaps. Training analysts remains valuable in regions where road ecology is still an emerging field and specialist resources are limited. Moreover, linking research outcomes and innovations (B9 and B10) could support more thorough impact assessments and the definition of effective mitigation by environment agencies. The gap between researchers and decision-makers is a crucial issue: while good quality information is available to support proper mitigation allocations, it is often not integrated into the decision-making process. Improved cross-sector collaboration within environmental licensing would also help overcome these barriers (Freitas et al., 2017; Teixeira et al., 2016).

We believe that the paths to solutions given by specialists represent meaningful results. We consider most of the proposed solutions hypothetical possibilities, but in most cases, potential solutions for addressing mitigation measures are not available for decision-makers. It is worth noting that one well-known path for ensuring mitigation measures, the use of legal means for pressuring road managers (B8), received a low level of agreement between specialists, especially when the effects of it as a barrier (mainly the slowness of the process) were also considered to be less important compared to other barriers. Moreover, solutions linked to actual inclusion of mitigation measures in concessions, as well as active co-production with different stakeholders presented a high level of agreement between specialists. This demonstrates the need for engaging in a new paradigm of conservation, co-production as a path for a more sustainable scenario (Cooke et al., 2022; Pereira et al., 2020; Teixeira et al., 2016).

Considering our case study, we were able to understand the effects of a few barriers in practice. For instance, we concluded that B1 and B2 were, to a certain degree, overcome, but only after a public motion. Considering the conditions in which the implementation took place, however, it is still difficult to affirm that both barriers were in fact overcome in practice. We believe that the obligation of the infrastructure agency to install the measure had an impact on its quality. For B3, the challenge was inadequately addressed. Research indicates that fence segments should be at least 5 km in length to maximize effectiveness, as Huijser et al. (2016) demonstrated. Shorter fences, like those installed in this case, are often ineffective in reducing collisions. The efficacy of longer fencing segments is also supported by Rytwinski et al. (2016), whose meta-analysis confirmed that longer fences substantially reduce WVCs by preventing wildlife from entering the road in high-risk areas. The fence would have been longer and made with stronger material, in consultation with the local population, ensuring fewer problems with long-term maintenance. In terms of B4, we believe that if mitigation measures preceded the paving of the road, we would see better outcomes for conservation. Another important factor is the fame of this road as "the death road" is largely sustained by the media reporting fatalities over the years (Morais et al. in preparation). This pressure combined with public opinion (B5) were important for moving agencies forward from inertia.

Analysts from the environment agency in countries such as Brazil in the Global South often face high workloads and diverse demands, with limited time to access scientific literature. Additionally, language barriers make accessing relevant research more challenging. If these analysts had a solid background in road ecology, they might have prevented the installation of poorly planned fence segments (B6).

Another important consideration from the case study highlights how this communication barrier also reflects broader planning and decision-making challenges (B7). One issue reported was that community members damaged fencing structures to access nearby streams, suggesting a lack of initial consultation that might have identified these needs earlier in the planning process. If there had been a preliminary phase that included local community input, allowing their perspectives to influence the placement of fences, this conflict might have been minimized. Additionally, a communication and education program tailored to the community's context could have helped build understanding and support for the project's objectives. This example underscores that future planning should prioritize community needs alongside technical considerations. Moreover, if all research findings had been fully considered and applied when implementing these measures (B9), we could expect improved outcomes. We also believe that for barriers like B10, the challenges would only increase during the execution phase. Recently, BR-262 received an entirely new plan for mitigation, and one of the possible challenges includes innovative ideas for ensuring that fences work even when Pantanal areas flood. It is important to note that political will (B2) and connection between road manager and environmental agency (B4) are needed to implement this new plan in the next years.

In Brazil, addressing the 10 key barriers to mitigating WVCs is crucial for preserving its rich biodiversity across diverse biomes. The study emphasizes the necessity of overcoming challenges such as the lack of public policies, bureaucratic obstacles, financial constraints, and insufficient expertise. It also highlights the importance of inclusive strategies that incorporate community engagement and stakeholder collaboration to develop effective mitigation measures, as demonstrated by the BR-262 case study.

More broadly, our findings offer a globally applicable framework for analyzing and addressing the impacts of roads on wildlife. The emphasis on cross-sector collaboration, stakeholder engagement, and the integration of social, economic, political, and technical considerations in mitigation efforts provides valuable insights for developing sustainable transport infrastructures worldwide. This study represents one of the few attempts to document barriers to implementing mitigation measures for WVC, contributing to a structured understanding of these challenges within road ecology. Although our methodology has proven effective, we acknowledge that there is room for improvement, particularly in expanding the range of perspectives included. This approach could be applied globally, recognizing that barriers may vary considerably across different contexts and scales. Incorporating a broader range of stakeholders, including more professionals from public agencies and road managers, could provide a more comprehensive view of both technical and social barriers. Additionally, perspectives from outside traditional ecological fields could enhance our understanding of interdisciplinary challenges and promote more effective co-produced solutions.

We believe that barriers are part of a whole socio-ecological system that comprises impacts from infrastructures. From this perspective, we highlight the role of stakeholders in effecting positive outcomes for conservation, similarly to what is found in fields such as water governance and fisheries (Bodin, 2017; García & Bodin, 2019; Mancilla Garcia & Bodin, 2020). Barriers to implementing WVC mitigation measures are still relatively similar to those in other crucial environmental fields, and as such, we can learn from other examples to ensure that impacts on roads do not continue to increase.

Finally, through the definition and investigation of barriers, we were able to highlight important contributions. First, we used a simple approach and were able to obtain a useful overview of challenges and paths to overcome them. The approach is rather flexible and could be expanded to similar cases, such as linear infrastructures and even water transportation impacts or dams. Regarding our case study and the application of the barriers concept to WVC mitigation, we believe that we can highlight as a lesson learned the importance of public engagement combined with quality information and co-production. Barriers cannot be overcome unless stakeholders are completely invested in the process and societal sectors are fully present.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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