CONTRIBUTED PAPER

Prioritizing human safety and multispecies connectivity across a regional road network

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Abstract

The intersection of wildlife and people on roads raises two critical issues: the barrier and mortality effects of roads on wildlife and risks to people from animal-vehicle collisions (AVCs). Road mitigation decisions are typically made at the discretion of transportation departments that are mandated to primarily address motorist safety. Therefore, prioritization of road sections for mitigation currently focuses on identification of spatial clusters of AVCs. We sought to understand if AVC clusters align with multispecies connectivity across roads to accurately identify multipurpose mitigation hotspots. We developed a decision-support tool based on weighted priorities for mitigation planning across 7,900 km of roads over an 84,000-km^2 area of southern Alberta, Canada. To assess alignment, we built functional connectivity models for four focal species (prairie rattlesnake, grizzly bear, mule deer, and pronghorn) and a species-neutral structural connectivity model. We integrated AVC risk and wildlife connectivity indices into Mitigation Priority Indices that varied the weighting of individual indices. Our results demonstrated poor spatial alignment between road sections of high motorist safety risk and those of high value for wildlife connectivity. Transportation planning would benefit from integrating motorist safety risk and wildlife management needs to prioritize mitigation neighborhoods along roadways.

KEYWORDS
animal-vehicle collision, functional connectivity, grizzly bear, human safety, mule deer, pronghorn, rattlesnake, structural connectivity, transportation planning, wildlife management

1 | INTRODUCTION

The intersection of wildlife and people on roads raises two critical issues: (a) effects of roads on the movement and mortality of wildlife, and (b) effects of vehicle collisions with wildlife on motorist safety and property (Ceia-Hasse, Navarro, Borda-de-Água, & Pereira, 2018; Conover, Pitt, Kessler, DuBow, & Sanborn, 1995; Fahrig & Rytwinski, 2009). Maintaining wildlife movement across road networks is an important conservation strategy to sustain ecological connectivity (Forman et al., 2002; Taylor, Fahrig, & With, 2006). Direct mortality of wildlife

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from animal-vehicle collisions (AVCs) can have population-level effects on species (Jackson & Fahrig, 2011). For example, in the Canadian province of Alberta, collisions with vehicles are one of the main causes of mortality for two provincially threatened species, the grizzly bear (*Ursus arctos*) and prairie rattlesnake (*Crotalus viridis*) (Alberta Environment and Parks, 2016a, 2016b). Additionally, roads, associated infrastructure, and vehicle traffic fragment the landscape and may reduce habitat availability or quality, alter predator–prey interactions, and reduce viability of wildlife populations through genetic isolation (Fahrig & Rytwinski, 2009; Forman et al., 2002; Frissell & Trombulak, 2000; Jakes, Jones, Paige, Seidler, & Huijser, 2018; Seiler, 2004). The consideration of connectivity in regional road planning is increasing in a number of jurisdictions (Ament et al., 2019). For example, managing for wildlife connectivity was recently highlighted by U.S. Department of Interior Secretarial Order 3362 to facilitate migration of large game animals in Western U.S. states where roads were identified as the primary barrier to maintaining functional connectivity for mule deer, elk, and pronghorn (Secretary of the Interior, 2019). In British Columbia, Canada, road closures are being used to reduce human-bear conflict and promote the safe movement of animals through the landscape (Mowat, 2017).

Motorist safety risk and societal costs associated with AVCs are important considerations for transportation planners. Across Canada, it is estimated that six large mammals are involved in an AVC per hour (L-P Tardif and Associates 2003). In the U.S., AVCs have doubled in frequency since the 1990s, with increases in both motorist fatality rate and frequency of AVCs per vehicle mile traveled (Sullivan, 2011). AVCs represent 4–5% of all collisions reported in the U.S., and a much higher percentage in some rural areas. In Alberta, Canada and Sweden, AVCs are responsible for 50 and 60% of collisions in rural areas, respectively (Alberta Transportation, 2017; Magioli et al., 2016; National Highway Traffic Safety Administration, 2003; Seiler, 2004). There are also significant economic costs to society from AVCs, which include monetary expenses associated with human injury or death and damage to public or private property. In Canada, ~45,000 ungulate-vehicle collisions per year are estimated to cost more than U.S. $281 million (Huijser, Duffield, Clevenger, Ament, & McGowen, 2009).

Numerous measures have been adopted in road construction to address the negative outcomes of road-wildlife interactions. Measures may be used independently or in concert to exclude wildlife from the road surface by using fencing, improving safe movements across the road using crossing structures (i.e., culverts, underpasses, or overpasses), or providing drivers with advanced warning of wildlife on or near the road (Bissonette & Rosa, 2012; Glista, DeVault, & DeWoody, 2009; Huijser et al., 2008, 2009). Financial costs of crossing structures and associated fencing are important considerations for transportation departments (Glista et al., 2009). Because road impacts on wildlife tend to be widespread, and effective mitigation measures are expensive, it is important to maximize the ratio of benefits to costs of road mitigation (Huijser et al., 2008; Polak, Rhodes, Jones, & Possingham, 2014). Identifying effective locations in which to pursue such interventions is one of the most important considerations, particularly if environment and transportation agencies need to address the benefit/cost ratio of mitigation alternatives in each project (Clevenger & Waltho, 2000; Ford, Clevenger, Huijser, & Dibb, 2011).

Alberta follows a common approach to identify locations for mitigation in which priorities are established by identifying spatial clusters of AVCs along the road networks (Alberta Transportation, 2017; Bíl, Kubeček, Sedoník, & Andrášik, 2017). However, it is unclear whether selecting locations for mitigation measures based solely on spatial patterns of AVCs addresses wildlife connectivity needs (Boyle, Litzgus, & Lesbarrères, 2017), as research in the U.S. Northern Rocky Mountains suggests that AVC clusters and predicted wildlife movement corridors exhibit little spatial overlap (McClure & Ament, 2014).

AVC hotspots (road sections with a higher proportion of AVCs than other road sections) indicate where risk to motorist safety from wildlife is highest, and also where impacts of roads on wildlife via direct mortality are highest. Yet they do not necessarily indicate where roads have the greatest influence on wildlife connectivity. Locations where roads intersect optimal movement corridors for wildlife may have few recorded AVCs if the characteristics of the road (e.g., width, traffic volume, presence of physical barriers such as fencing) prevent most individuals from attempting to cross, but these are potentially important locations for mitigation measures to facilitate connectivity (Ascensão et al., 2019; Clarke, White, & Harris, 1998). Locations where wildlife corridors are intersected by low-volume roads that are safely crossed by many individuals are also unlikely to be AVC hotspots, but these too, may be important locations for transportation planners to consider in order to preserve existing crossing opportunities as traffic volumes increase or roads are expanded. AVC data may also have limited value for assessing road impacts to wildlife populations that exist at low densities, as well as those impacted by "ghost effects" wherein previous road mortality levels have resulted in localized extinction (Ascensão, Kindel, et al., 2019; Ford & Fahrig, 2007).

These limitations of AVC hotspot analyses exemplify the need for additional information needed to accurately

evaluate locations where wildlife connectivity is restricted along road networks. Connectivity modeling can help fill this information gap by mapping predicted movement patterns of wildlife across a landscape, allowing identification of optimal locations for wildlife to cross roads. Structural connectivity models consider only the configuration and composition of the landscape, independent of a species' response (Krosby et al., 2015; Tischendorf & Fahrig, 2000), and can provide general information on movement patterns of the ecological community with minimal data requirements. Functional connectivity models incorporate a species' response to the landscape (e.g., dispersal behavior) and are used to predict species-specific movement across a landscape but typically require more data (Taylor et al., 2006). An enhanced approach for representing animal movement needs across a landscape is to develop functional connectivity models for a series of focal species that represent a broader range of species (Krosby et al., 2015).

Transportation planning and prioritization of road mitigation could benefit from integrating motorist safety risk and wildlife connectivity needs at the initial stages of planning to more accurately assess "mitigation neighborhoods"—road sections within the overall road network where mitigation should be considered (as opposed to fine-scale locations of specific mitigation sites). Here, we demonstrate a stakeholder- and data-driven process for integrating AVC data and connectivity modeling in a decision-support tool that identifies multi-purpose priority road sections (mitigation neighborhoods) based on both motorist safety and wildlife connectivity in southern Alberta. We worked directly with the provincial transportation agency (Alberta Transportation, hereafter: AT), the provincial fish and wildlife agency (Alberta Environment and Parks, hereafter: AEP), and environmental non-governmental organizations (NGOs) to understand: (a) where predicted wildlife movement pathways intersect the road network; (b) where motorist safety risk associated with AVCs is highest along the road network; and (c) whether and where wildlife connectivity and motorist safety risk align. We present a series of scenarios for prioritizing mitigation hotspots based on different management concerns.

2 | METHODS

2.1 | Study area

We focused on the southern region of Alberta (83,764 km^2), which includes 12% of the province's area and 7,900 km of provincial roads (Alberta Development Sustainable, 2008) (Figure 1). Southern Alberta supports
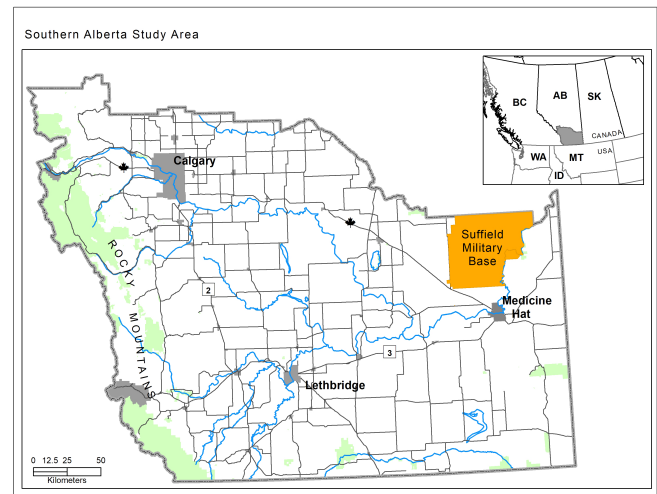

FIGURE 1 Southern Alberta study area with urban centers (dark gray polygons), highways (dark gray lines), parks (green polygons), and military base (orange polygon)

a diversity of ecosystems, including (from east to west) grassland, shrubland, mixed and coniferous forest, subalpine, and alpine (Natural Regions Committee, 2006). Natural landscapes in southern Alberta have been highly altered by farming, ranching, energy development, and forestry. Eighty percent of Alberta's Species At Risk occur in southern Alberta, and the region supports a majority of Canadian large-bodied mammals, including elk (*Cervus elaphus*), moose (*Alces alces*), bighorn sheep (*Ovis canadensis*), mule deer (*Odocoileus hemionus*), white-tailed deer (*Odocoileus virginianus*), pronghorn (*Antilocapra americana*), grizzly bear, back bear (*Ursus americanus*), wolverine (*Gulo gulo*), wolf (*Canis lupus*), coyote (*Canis latrans*), and cougar (*Puma concolor*) (Alberta Development Sustainable, 2008).

2.2 | Stakeholder engagement

In order to foster cross-agency collaboration and stakeholder engagement, we consulted with representatives from provincial government agencies (AT and AEP), environmental NGOs, and academics from universities and research institutes. At an initial stakeholder workshop, we developed a set of specific research questions and identified potential data sources, modeling approaches, and desired outcomes (Table 1). Stakeholders recommended that our analysis of wildlife connectivity include a species-neutral connectivity model (i.e., structural connectivity) and four species-specific functional connectivity models (prairie rattlesnake, grizzly bear, mule deer, and pronghorn) to represent connectivity for the southern Alberta ecological community as a whole. Focal species were

TABLE 1 Conservation problem solving with examples at each step based on our process of improving road wildlife mitigation planning

Step	Example of action
Define conservation problem	Impacts of roads on wildlife movement need to be better integrated into road mitigation decision-making.
Develop research questions	Where does wildlife connectivity intersect with the road network? Where is motorist safety risk a concern along the road network? Do important road sections for wildlife connectivity and motorist safety risk align?
Identify and engage stakeholders	Stakeholders included Alberta Transportation, Alberta Environment and Parks, environmental NGOs, universities, and research institutes.
Identify appropriate models and indices	Stakeholders identified need for five connectivity models and three motorist safety indices.
Acquire data and expert knowledge	Engaged other researchers working on connectivity modeling for species of concern (e.g., pronghorn connectivity model provided by PhD student).
Develop models and indices	Developed five connectivity models and obtained two AVC datasets. Converted datasets and models to AVC and connectivity indices and compared indices for correlation and areas of spatial alignment.
Develop overall prioritization indices	Created a set of mitigation priority indices (MPI) that consider a combination of high AVC risk and connectivity values to identify priority road sections for mitigation.
Review indices and prioritization results	Stakeholders reviewed modeling results and indices and provided weighting to prioritize road sections for mitigation using an analytical hierarchy process (AHP).
Integrate results into policy and planning	Developed recommendations on how to better incorporate wildlife connectivity into highway planning.

selected to represent different management objectives and data availability: mule deer is the large mammal species most commonly involved in AVCs and occupies most of the region (Alberta Transportation, 2017); pronghorn is a

Species At Risk in Alberta that occupies native grasslands, migrates long distances, and avoids roads (Gavin & Komers, 2006; Jakes, 2015; Jakes et al., 2018; Jones, Jakes, Eacker, & Hebblewhite, 2020); grizzly bear and rattlesnake are both Species At Risk and susceptible to road mortality (Alberta Environment and Parks, 2016a, 2016b). Grizzly bears occur only in the western portion of the study area within the Canadian Rocky Mountains and along the foothills, while rattlesnakes occur in the eastern portion of the study area.

2.3 | Road sections

We used stretches of road between consecutive 1-km highway reference markers (hereafter: "road sections") as the spatial unit of analysis when assessing motorist safety risk and wildlife connectivity value across the road network. The majority of road sections were 1 km in length, although some sections were longer or shorter, particularly near intersections.

2.4 | Assessing motorist safety risk

We assessed the spatial distribution of motorist safety risk associated with AVCs using records from two data sources: (a) Royal Canadian Mounted Police (RCMP) AVC data ($n = 9,866$ records) from 2010 through 2014; and (b) Alberta Government Solicitor General Enforcement (ENFOR) carcass data ($n = 408$) documented by conservation officers as "roadkill" from April 2014 through July 2017. RCMP data are reported by motorists involved in AVCs and include information on the wildlife species involved and the collision location estimated to the nearest km, while ENFOR data are reported by an officer and include GPS coordinates of the wildlife carcass. From each of these data sources, we created three AVC indices (Table S2, Figure S1) by counting the number of AVCs recorded within each road section within the study area. To account for locational uncertainty of AVC records (Gunson, Clevenger, Ford, Bissonette, & Hardy, 2009), the value for each road section was calculated as the average count within that section and its two neighboring sections (Shilling & Waetjen, 2015). Finally, we divided these counts by the total length of the focal road section and neighboring sections to adjust for variation in road section length.

We calculated a version of the RCMP-based AVC index that adjusted for traffic volume (annual average daily traffic, AADT) within road sections to provide a measure of AVC risk per motorist (hereafter: "traffic adjusted RCMP-based AVC index"). All AVC indices were rescaled from AVC rate (count per km) to range

from 0 to 1 to facilitate comparisons among indices. Because the distributions of values for AVC indices were highly skewed, with the vast majority of road sections having low values and only a handful of road sections having very high values, we converted AVC index values to percentiles to better capture the variation within the lower portions of the distributions.

2.5 | Assessing connectivity

We used connectivity models to infer where wildlife was most likely to move across roads in the region. We used Linkage Mapper 2.0 software (McRae, Dickson, Timothy, & Shah, 2008) to model species-neutral structural connectivity and species-specific functional connectivity. We made use of existing data and models (Table S1) where possible to develop the two inputs required by Linkage Mapper for each model: (a) a landscape resistance surface representing the relative cost of moving through each landscape cell as a function of its environmental characteristics (e.g., terrain, cover type, degree of human modification); and (b) locations of focal nodes, the points within the landscape among which animal movement is modeled (typically protected areas or resource patches). Connectivity model outputs were already available for pronghorn (Jakes, 2015) and thus did not require the development of resistance surfaces or focal nodes. Resistance surfaces for all focal species included a barrier effect of roads (Table S1), which was assumed to be constant for all road types and traffic volumes.

To develop focal nodes used in models for structural connectivity, prairie rattlesnake, and mule deer, the study area was subdivided into a "mesh" by the primary and secondary highways, and nodes were placed at the centroids of all mesh cells ≥ 500 km^2 (which approximated the 90th percentile of mesh cell areas). Focal nodes for grizzly bear were placed within secure habitat patches >5 km^2 as defined by Gibeau, Herrero, McLellan, and Woods (2001) and for pronghorn were placed in core habitat patches (Jakes, 2015).

For each connectivity model, we used Linkage Mapper to calculate least-cost corridors between all pairs of focal nodes within the study area. We then mosaicked these corridors to create a single composite raster map in which cell values represented the relative probability of movement through the cell. This method was intended to capture long-distance movement pathways or ecological flows among resource patches across the landscape while minimizing model sensitivity to placement of focal nodes (Marrotte & Bowman, 2017; Theobald, Reed, Fields, & Soulé, 2012) and reducing "halo effects" around focal nodes in model outputs (Koen, Bowman, Sadowski, & Walpole, 2014).

We created a connectivity index from each connectivity model output (i.e., raster map of connectivity value) by calculating the mean value of cells overlapping each road section (Table S2, Figure S1). We rescaled connectivity output values for each connectivity index such that values ranged from 0 to 1, with higher values representing greater predicted wildlife movement. As with the AVC indices, the distributions of connectivity index values tended to be highly skewed, so we converted connectivity index values to percentiles.

2.6 | Alignment of indices on the road network

We examined the degree of spatial alignment between motorist safety risk and wildlife connectivity value across the highway network. We used the structural connectivity index as our measure of connectivity because it was species-neutral and the most appropriate proxy for connectivity of the ecological community as a whole among our connectivity indices. We used RCMP-based AVC indices as our measure of motorist safety risk because it was generated from RCMP data that are most commonly used by Alberta Transportation to guide decisions on mitigation.

To quantify agreement among indices, we calculated Spearman's correlation coefficient between values of these two indices for road sections across the highway network. We also calculated the sum of the two indices for each road section as a measure of spatial alignment. Because both indices range from 0 to 1, road sections with high motorist safety risk and high connectivity value should have summed values close to 2. We mapped the summed values to determine whether and where such conditions exist along the road network.

We used these same measures (Spearman correlation and summed values) to examine the degree of agreement between the RCMP-based AVC index and traffic-adjusted RCMP-based AVC index. Road sections with high RCMP-based AVC index values represent areas with the highest number of AVCs and therefore greatest total costs to motorist safety and property. Road sections with high traffic-adjusted RCMP-based AVC index values represent areas with the highest risk to motorist safety on a per-motorist basis, regardless of the total number of AVCs that occur in the area—an important consideration for people living in less populated, rural areas.

2.7 | Prioritizing road sections for mitigation

We created a set of scenarios representing a range of plausible options for prioritizing road sections for mitigation,

including scenarios emphasizing motorist safety, emphasizing wildlife connectivity, or representing a mixture of the two (Figure S1). For each scenario, we assigned a weight to each AVC or connectivity index such that weights summed to 1 (Table S3), and we calculated the weighted mean of indices for each road section as an overall Mitigation Priority Index (MPI). We also developed a stakeholder-based MPI at a second stakeholder workshop using an analytical hierarchy process (AHP) (Saaty, 1977). The AHP is a mathematical method for analyzing complex decisions using pairwise comparison ratios and has been effectively used to inform conservation decision making (Clevenger, Chruszxz, Gunson, & Wierzchowski, 2002). Workshop participants assigned a weight to each AVC or connectivity index such that weights summed to 1, and we calculated the weighted mean for each road section as a stakeholder-based MPI.

We further refined our MPI results by applying a traffic volume filter to better focus mitigation planning on road sections that are expected to be problematic for wildlife. Impacts of traffic volume on wildlife can be generally classified as low where species cross roads and are at low risk of AVCs, moderate where species cross roads but are at higher risk of AVCs, and high where species no longer cross roads and exhibit avoidance behavior, although the specific traffic volume thresholds that define these classes vary by species (Gagnon, Theimer, Dodd, Boe, & Schweinsburg, 2007; Litvaitis & Tash, 2008). If effects of traffic volume are not considered during mitigation planning, the unfiltered MPI results may suggest higher priority than is actually warranted for road sections where models predict high wildlife connectivity value but current traffic volumes are too low to significantly impact wildlife via AVCs, barrier effects, or avoidance behavior. Road sections in our study area range in traffic volume from 50 to 100,000 vehicles per day. For this study, we selected a low-impact traffic volume threshold of 500 vehicles per day and removed road sections below this threshold from further consideration for road mitigation planning. This threshold value was derived from a summary of thresholds for different taxonomic groups by Charry and Jones (2009), and it represents an approximate traffic volume beyond which a road has some impact on carnivores, ungulates, birds, amphibians, and reptiles.

3 | RESULTS

3.1 | Identification of road sections that intersect with wildlife connectivity

Road sections with highest structural connectivity values tended to be located in the western portion of the study area on public land, in the eastern portion on roads located around a large military base (Canadian Forces Base Suffield), and in the southeastern corner on predominately public land (Figure 2). In the central portion of the study area, which consisted primarily of private lands that were more fragmented by human activities, structural connectivity was largely confined to riparian areas associated with large river systems.

Areas of high connectivity value for focal species were limited by species' geographic ranges and locations of large habitat patches. Rattlesnakes occur only in the eastern portion of the study area, and road sections with high connectivity value for rattlesnakes were located around large, intact blocks of habitat near the City of Lethbridge, Suffield Military Base, and along the Canada/U.S. border (Figure 2).

Road sections that intersected with area of high connectivity value for grizzly bears were located along paved highways along the eastern edge of grizzly bear range in Alberta, and where roads bisected the Canadian Rocky Mountains in low elevation east–west corridors (Figure 2).

Mule deer occur across the study area, and the mule deer connectivity model (Figure S2) indicated movement throughout the study area with a limited number of pinch points, as indicated by straight-line paths between focal nodes, with the exception of higher connectivity values associated with large river systems. The straight lines between focal nodes suggest the model could be influenced by node placement and low variability within the cost surface and may have limited utility for prioritizing road sections.

Road sections that intersected with high connectivity values for pronghorn were located throughout the eastern portion of Alberta, mainly on roads between public lands in the southeastern corner of the study area and Suffield military base (Figure S2).

3.2 | Identification of road sections with high AVC risk

Road sections with high AVC risk (determined by RCMP-based AVC index) were most common on the fringes of urban centers, where traffic volumes are higher and deer populations are abundant. Road sections with high AVC risk per motorist (determined by traffic-adjusted RCMP-based AVC index) were most common away from large urban centers along rural road sections, where animal movement across lower-volume roads is likely more frequent based on road sections with higher structural connectivity values (Figure S3). There was a moderate correlation between RCMP-based AVC index and traffic-adjusted RCMP-based AVC index values ($r =$
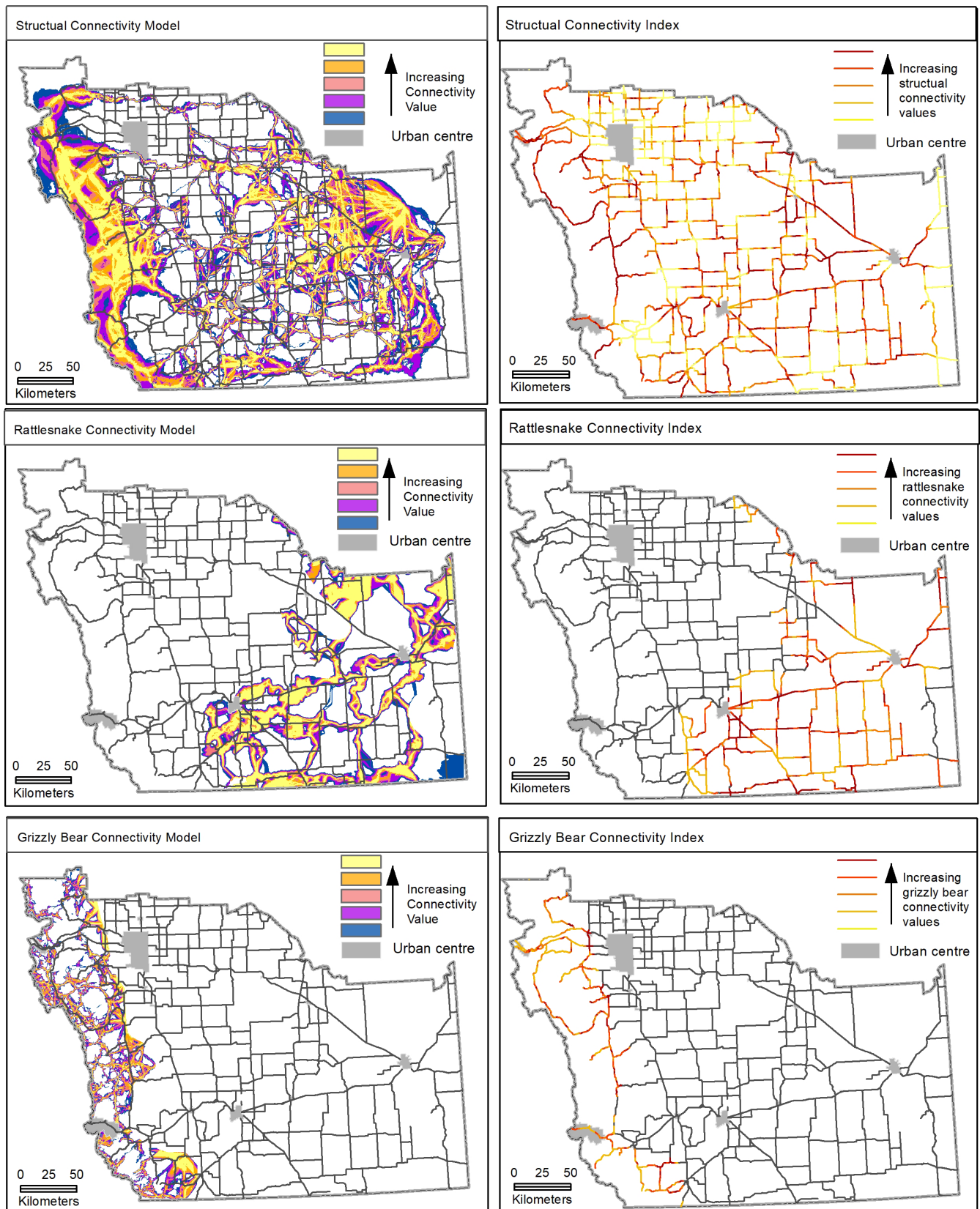
FIGURE 2 Connectivity model output (left column) and resulting connectivity index along southern Alberta's road network (right column) for structural connectivity (top row), rattlesnake connectivity (middle row), and grizzly bear connectivity (bottom row). Roads shown in gray in right column were outside of the connectivity modeling spatial extent for a given species and not assigned connectivity index values

.6), with spatial alignment of high values occurring predominately in road sections within the eastern portion of the study area along two-lane highways (Figure S3).

3.3 | Alignment of AVC risk and connectivity road sections

Road sections with high structural connectivity values occurred in rural areas near large habitat blocks or where large river systems intersected the road network. Road sections with high AVC risk occurred around large urban centers and on high-volume roads (Figure 3). There was a weak correlation between RCMP-based AVC index and structural connectivity index values ($r = -.028$), with a

limited number of aligned road sections with high values for both AVC and connectivity indices occurring most commonly in the southwest corner of the study area (Figure 3).

3.4 | Prioritizing road sections to identify mitigation neighborhoods

The series of mitigation priority index (MPI) scenarios established to inform road mitigation yielded different spatial patterns of mitigation priority. Scenarios emphasizing AVC risk resulted in prioritization of road sections around large urban centers, while scenarios emphasizing connectivity resulted in prioritization of road sections
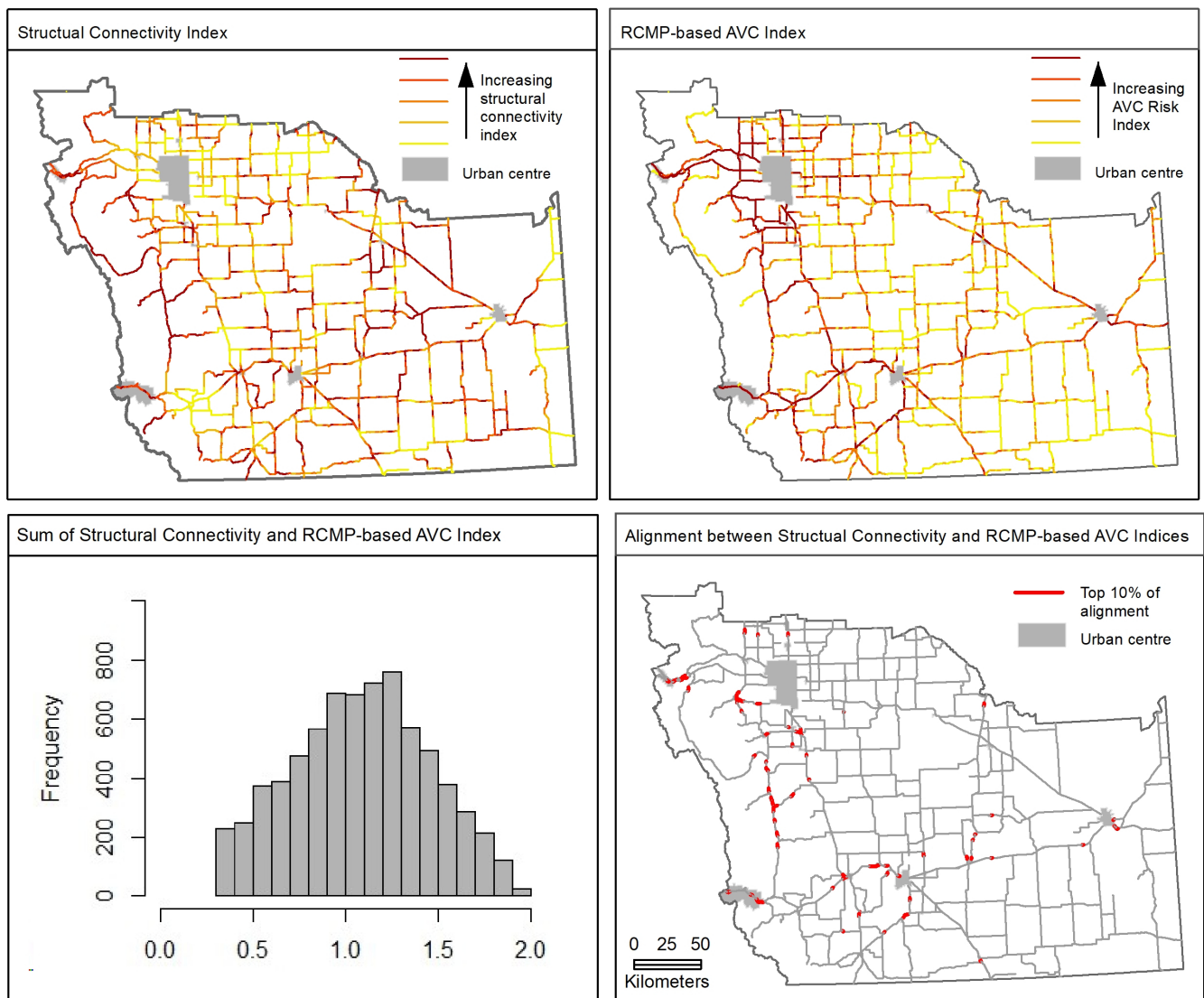

FIGURE 3 Structural connectivity value of road sections (top right); AVC risk of road sections (top left); histogram of summed percentile values from the two indices, indicating poor agreement between high values of the two indices (bottom left); and road sections with highest 10% of summed index values (i.e., values ≥1.8, highlighted in red) (bottom right)

across the road network in more rural areas (Figure 4). The scenarios with equal emphasis on connectivity and AVCs resulted in prioritization of road sections in the western portion of the study area, where large river systems cross the road network, and around large urban centers (Figure 4).

Stakeholder-derived weights established using the AHP scored AVCs (88%) as more important than connectivity (12%) for prioritizing locations of road mitigation measures (Figure S4). In addition, stakeholders weighed structural connectivity as the most important consideration for prioritization of connectivity indices. The prioritization of the road network based on stakeholder-derived weights was similar to the AVC index prioritization in that priority road sections tended to be those with the highest number of total AVCs.

4 | DISCUSSION

Road mitigation decisions are typically made at the discretion of jurisdictional transportation agencies, which are mandated to address motorist safety. For this reason, prioritization of road sections for mitigation tends to focus on identification of spatial clusters of AVCs. In contrast, threats to wildlife connectivity typically fall within the purview of environment or wildlife agencies, whose primarily responsibility is managing game species and overall biodiversity. To accommodate these diverse mandates, we developed a decision-support tool that represents both motorist safety and wildlife connectivity

along the road network, tested for alignment between AVC and connectivity indices, and presented multi-purpose road mitigation prioritization results based on a series of scenarios representing different management objectives. The design of our decision-support tool was driven by stakeholder engagement; two government agencies, academic researchers, and NGOs offered guidance on how to quantify AVCs and connectivity along the road network, and also how to balance these concerns when establishing priorities to identify mitigation neighborhoods. Our research findings and recommendations to conservation practitioners and transportation planners are summarized in Table 2 and described in further detail below.

4.1 | Cross-agency planning early in road planning process

Transportation departments are mandated to ensure the safe movement of people and goods, and therefore focus on motorist safety aspects of road and wildlife interactions (Lesbarrères & Fahrig, 2012). This leaves significant gaps in planning for road mitigation to maintain wildlife populations. Cross-agency collaboration between transportation and environment agencies early in the planning process is an important step toward incorporating wildlife into transportation planning initiatives. Transportation planning often takes place many years before road upgrades or new roads are established. Early coordination between agencies also allows environment agencies
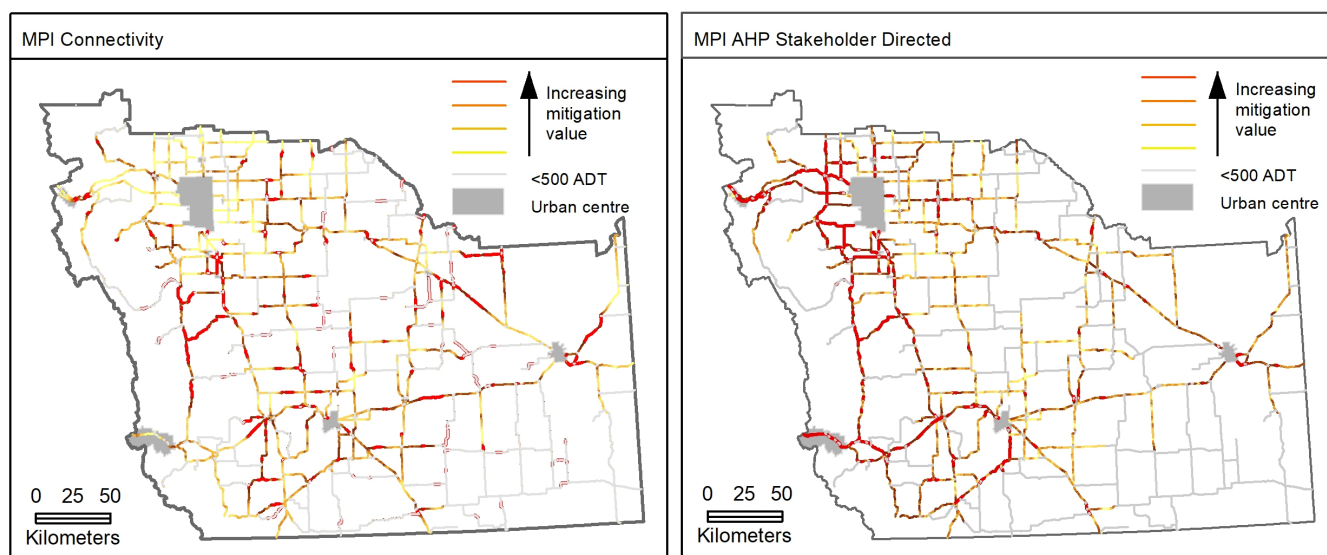

FIGURE 4 Road Mitigation Priority Indices (MPI) based on two scenarios: the MPI_C scenario (Table S3) emphasizing wildlife connectivity with equal weight for all connectivity models (right column); and the MPI_Stakeholder scenario based on weights derived from stakeholders though an AHP (left column)

TABLE 2 Key findings and recommendations for provincial and state agencies mandated to address AVCs and connectivity along roads

Discussion theme	Findings	Recommendation
4.1 Multi-agency engagement	Provincial transportation and environment departments have different mandates, but both can benefit from road mitigation.	Cross-agency collaboration early in the planning process is an important step toward incorporating wildlife into transportation planning.
4.2 Spatial alignment of metrics	Road sections with highest total AVCs and highest per-motorist AVCs exhibit only moderate spatial overlap.	Transportation planners should consider both individual motorist safety risk and total cost of collisions, and how they overlap, in prioritization of road sections for mitigation.
	Road sections with high rates of AVCs and high structural connectivity values exhibit poor spatial overlap.	Transportation planners should consider wildlife connectivity needs in addition to motorist safety risk in transportation planning.
4.3 Identification and prioritization of mitigation neighborhoods	Areas of agreement between derived road indexes can be represented using the mitigation priority index decision-support tool	Given high cost associated with road mitigation, prioritization is an important component of transportation planning and would be most effective where different indices align.
4.4 Stakeholder perceptions	Though roads have well-described impacts on biodiversity, project stakeholders placed much greater emphasis on motorist safety than on wildlife connectivity concerns.	Education regarding investment in conservation strategies relating to roads, species conservation, and land use planning is needed.
4.5 Evolution of transportation planning	Traditional approaches to planning for road mitigation focus on roads sections with high rate of AVCs.	Transportation planning and prioritization of road wildlife mitigation would benefit from widening the lens and integrating motorist safety risk and wildlife population needs.
	Priority species for which road mortality and/or population fragmentation are concerns should be considered in transportation planning.	AVC and connectivity indices for individual priority species should be developed to support finer-scale research into specific locations for mitigation.
	Government agencies make decisions in a provincial context, so data need to be provided at the appropriate spatial extent and resolution.	Standardized road indices for AVCs and connectivity should be developed to enable the systematic identification of road sections for mitigation at transportation departments' operational scale.

to prioritize road ecology research on roads earmarked for upgrades.

4.2 | Alignment of road mitigation metrics

Road mitigation planning and prioritization focuses on identification of road sections with high AVCs, and

therefore we sought to understand if there is alignment between AVC hotspots and wildlife connectivity modeling. AVC data enabled us to identify where collisions occurred most frequently along the road network, representing areas of both high risk to motorist safety and direct wildlife mortality. Understanding what influences the location of AVCs is complicated by multiple factors, including but not limited to taxonomic group, traffic volume, seasonality, and landscape and site-specific features

(Seo, Thorne, Choi, Kwon, & Park, 2013). We found that AVCs involving large-bodied mammals were most common around large urban centers where a combination of high traffic volume and abundant deer populations intersect to create a "perfect storm" for AVCs, a pattern that has been reported elsewhere (Olson, 2013). However, when normalized by traffic volume, AVCs were more common along rural road sections, which represent locations where risk to individual motorist safety (i.e., per-motorist risk) is highest. We recommend that transportation planners consider both individual motorist safety risk and total collision risk—and particularly areas of strong spatial alignment between the two—when prioritizing road sections for mitigation.

We observed poor spatial alignment between road sections of high motorist safety risk and those of high value for wildlife connectivity in southern Alberta, which is consistent with findings from previous studies in other locations. For example, McClure and Ament (2014) reported only a small number of road sections where carcass hotspots aligned with predicted movement corridors for carnivore species in Montana and Idaho. Neumann et al. (2012) found that moose-vehicle collision hotspots and moose crossing locations predicted by connectivity models did not align in Sweden, and that traffic volume and road site characteristics best explained moose-vehicle collision patterns. These findings illustrate the complexity of planning for road mitigation to address wildlife connectivity and motorist safety, as well as the limitations of only considering AVC metrics.

Our results also demonstrate the value of using multiple connectivity modeling approaches. Models for pronghorn, grizzly bear, rattlesnake, mule deer, and structural connectivity each suggested different patterns of connectivity value across the landscape and road network. By combining a species-neutral model with species-specific models for focal species that encompass a variety of geographic distributions, habitat preferences, and dispersal capabilities, we captured movement corridors that would potentially be overlooked if only one model was used.

4.3 | Identification and prioritization of road sections for mitigation

A key objective of this study was to develop a process for prioritizing road mitigation measures across Alberta's highway network that incorporated motorist safety and wildlife connectivity. The MPI scenarios we created achieve this by highlighting where there is spatial alignment between indices, indicating road sections that meet both transportation and wildlife management agency mandates, while enabling practitioners to weight indices

depending on their own interests. Our results for different MPIs are a useful starting point for prioritizing road mitigation efforts across southern Alberta, but transportation planners and conservationists may want to consider addition refinements of these priorities to maximize cost effectiveness or represent additional objectives.

We presented one such refinement based on applying a traffic volume filter to eliminate road sections that present relatively low risk to wildlife due to limited vehicle traffic. We based our traffic volume threshold on guidance from Charry and Jones (2009), who summarized road impacts and recommended thresholds that vary by species. For example, roads begin impacting amphibians and reptiles at 100–500 vehicles per day, increase in severity between 1,000 and 6,000 vehicles per day, and act as complete barriers above 6,000 vehicles a day. In contrast, roads begin impacting ungulates at 500 vehicles per day and are thought to act as complete barriers at 10,000 vehicles per day (Charry & Jones, 2009; Seiler, 2005). Our results could be further refined by accounting for species-specific responses to traffic volume and other environmental characteristics; for instance, previous research has explored when and where animals are most at risk by developing generic models to assess different taxonomic group sensitivities to traffic volume, road type, noise level, and site characteristics (Fahrig & Rytwinski, 2009; Jaeger et al., 2005; Litvaitis & Tash, 2008). Future iterations of the decision-support tool could also include additional focal species and more realistic resistance surfaces for connectivity modeling that account for road characteristics and locations of existing infrastructure that facilitates safe wildlife passage. For instance, outputs of connectivity models using resistance surfaces that incorporate traffic volume effects could be compared with outputs of models using resistance surfaces that exclude traffic volume effects; such comparisons could help identify locations where wildlife would ideally cross roads but are currently impeded by vehicle traffic, which may be particularly effective locations for restoring connectivity with road mitigation measures. Prioritization results should also be reassessed as traffic conditions along southern Alberta's road network change over time; some road segments that were filtered from our analysis due to low traffic volume may eventually warrant reconsideration for mitigation measures as traffic volume along these sections increases.

4.4 | Stakeholder perceptions

The MPI developed by stakeholders in this study heavily weighted AVC risk over connectivity concerns. Based on participant discussions, this weighting reflected the

perception that political, social, and financial support for motorist safety far outweighs current support for wildlife connectivity; thus, mitigation measures may be more likely to be implemented if motorist safety is used as a justification. However, given the increasingly recognized and well-described impacts of roads on biodiversity, we suggest that educating stakeholders, policy-makers, and the public about investment in road-related conservation and land-use planning strategies is a necessary and worthwhile exercise. Other jurisdictions have invested in road mitigation to facilitate animal movement across roads, in some cases designing mitigation measures for the benefit of individual species. For example, two overpasses were developed along Highway 191 in Wyoming to support pronghorn movement across a road (Sawyer, Rodgers, & Hart, 2016).

4.5 | Evolving road mitigation planning

Alberta currently has no formal mechanisms to ensure wildlife considerations are included in transportation planning, although the wildlife management agency may comment on individual projects. Other jurisdictions are moving toward improved coordination between environment and transportation agencies. Newly established state policy in New Mexico, California, and New Hampshire has enabled integration of transportation and environment agencies' mandates into transportation planning (Ament et al., 2019). To support policy implementation, numerous U.S. states have also developed statewide connectivity plans that can aid in the prioritization of road sections for mitigation to improve permeability for large-bodied mammals (Clevenger, 2012). Our approach for developing wildlife connectivity indices for a series of focal species closely aligns with the Washington Connect Landscape Initiative (Washington Wildlife Habitat Connectivity Working Group, 2010). We envision further opportunities for jurisdictions to follow the examples provided by these states and develop policy that enables the integration of wildlife concerns into transportation planning.

Our findings have important implications for conservation of priority species such as grizzly bear, prairie rattlesnake, and pronghorn whose conservation depends on mitigating the barrier effect of roads. AVC datasets alone are unlikely to include sufficient numbers of priority species observations to influence the location of AVC clusters or to generate species-specific clusters (Ford & Fahrig, 2007). Connectivity modeling may therefore play a critical role in identifying locations where movement pathways and roads intersect for species not well represented in AVC data (Ascensão, Mestre, & Barbosa, 2019).

Although the species assessed here represent an important starting point, additional species could be incorporated into the decision-support tool to ensure broader ecological representation.

We relied on connectivity models to identify road sections where multi-species movement is most likely to occur. Empirical observations of animal road crossings (e.g., camera trapping, telemetry, or track surveys) would provide more direct evidence of animal movement adjacent to and across roads; however, the costs of acquiring such data for multiple species at the operational scales of the agencies involved (i.e., at fine spatial resolution for the full provincial highway network) were not feasible for this study (Boyle et al., 2017). Instead, our results identify mitigation neighborhoods that agencies and researchers could examine in more detail with fine-scale animal-road interaction data to site individual mitigation measures, such as underpasses and wildlife exclusion fencing. For example, connectivity modeling across the TransCanada Highway for pronghorn is being complemented with fine-scale data collected by Pronghorn Xing, a citizen-science program in which participants report wildlife sightings along the highway network of the Northern Great Plains Ecosystem.

We hope the approach demonstrated in this study can serve as a model to support the identification of road mitigation neighborhoods in other jurisdictions where AVC and wildlife connectivity data are available and agencies are willing to work together. Such cooperation could yield benefits for both human and wildlife populations while increasing the efficiency of road mitigation efforts.

CONFLICT OF INTEREST
The authors report no conflicts of interest in this research.

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ETHICS STATEMENT

DATA AVAILABILITY STATEMENT

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