



# Differences in Spatiotemporal Patterns of Vehicle Collisions with Wildlife and Livestock

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## Abstract

Road ecology research has tended to focus on wildlife-vehicle collisions (WVCs) while omitting or failing to differentiate domestic (i.e., livestock) animal-vehicle collisions (DAVCs). This has limited our understanding of where, when, and how frequently DAVCs occur, and whether these patterns differ from those for WVCs. We used a 10-year collision data set for the U.S. state of Montana to compare temporal and spatial patterns of DAVCs versus WVCs at multiple scales. WVCs exhibited two diel peaks (dawn and dusk) versus only one prominent peak (late evening/early night) for DAVCs. Seasonal patterns of WVCs and DAVCs were broadly similar, but DAVCs exhibited a more pronounced late-fall peak. At the county scale, DAVCs were overrepresented relative to WVCs in most of eastern Montana and underrepresented in most of western Montana. WVC and DAVC hotspots did not show strong overlap at the 1-mile road segment scale. Our results suggest that DAVCs warrant greater attention, and they may represent a high priority for management and mitigation measures in some areas because (1) they can be locally common even when regionally rare, (2) they are more dangerous to motorists on a per-collision basis than WVCs, and (3) they can present a legal liability for livestock owners. Mitigation measures for DAVCs may differ from those for WVCs and require further development and testing. Future data collection efforts should include information not only on the location and timing of animal-vehicle collisions, but also on the species of animals killed.

**Keywords** Animal-vehicle collisions · Human safety · Livestock · Road ecology · Wildlife

## Introduction

Vehicle collisions with large animals are a frequent occurrence in many parts of the world (Farrell and Tappe 2007; Grilo et al. 2018; Jeganathan et al. 2018) and can result in animal mortality, property damage, and human injuries or fatalities (Bissonette et al. 2008; Huijser et al. 2008). In the United States, animal-vehicle collisions (AVCs) and associated human fatalities have increased by at least 50% since

1990, and an estimated 1–2 million AVCs with a total economic cost of \$8.4 billion now occur annually (Huijser et al. 2008; Sullivan 2011). With the length of the global road network expected to expand by 60% between 2010 and 2050 (Dulac 2013), the public safety risk and ecological threat posed by AVCs will continue to grow worldwide (Laurance et al. 2014).

Much of what is known about AVCs comes from the scientific discipline of road ecology, which has developed rapidly over the past few decades and seeks to understand and mitigate the impacts of roads on ecological systems (Spellerberg 1998; Forman et al. 2003; Van der Ree et al. 2015). One particular area of interest in road ecology research is vehicle collisions with wildlife species, especially large ungulates, such as whitetail deer (*Odocoileus hemionus*), mule deer (*Odocoileus virginianus*), elk (*Cervus canadensis*), and moose (*Alces alces*), which account for the vast majority of AVCs in North America (Huijser et al. 2008). Collisions with domestic livestock (e.g., cattle [*Bos taurus*], horses [*Equus caballus*], and sheep [*Ovis aries*]) are typically not differentiated in data

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collection systems by transportation departments, law enforcement personnel, natural resource agencies, or motor vehicle insurance claims. Although they are separated in some databases, livestock-vehicle collisions are often excluded from scientific analyses or lumped together with collisions involving wildlife. This lack of differentiation between domestic animal-vehicle collisions (DAVCs) and wildlife-vehicle collisions (WVCs) is also common among traffic safety studies conducted by transportation agencies and public health researchers, and it limits our understanding of where, when, and how frequently DAVCs occur, and whether these patterns differ from those for WVCs.

There are several compelling reasons for focusing greater attention on DAVCs and drawing clearer distinctions between DAVCs and WVCs. Firstly, DAVCs may be locally abundant despite representing a small percentage of all AVCs at broader scales. Anecdotal evidence suggests that DAVCs account for a significant component of AVCs and their associated human safety risks in some rural communities (Zaloshnja et al. 2003; Cramer and McGinty 2018). Even at the state or national level, DAVCs may contribute significantly to AVC risk; for instance, DAVCs account for 15 and 16% of AVCs in the U.S. states of California and Utah, respectively (Perrin and Disegni 2003; Huijser et al. 2008), and 80% of AVCs in Israel (Inbar et al. 2002). Secondly, DAVCs may present a greater risk to human health on a per-collision basis because the greater mass of livestock relative to most wildlife species can result in more severe collisions and greater likelihood of human injuries (Perrin and Disegni 2003; Huijser et al. 2008). Thirdly, optimal strategies for reducing collision risk may differ for DAVCs and WVCs. The design of mitigation measures (e.g., fencing, crossing structures, animal detection systems) and the identification of priority locations for their implementation should be guided by animal biology, behavior, and spatiotemporal patterns of AVCs—all characteristics that could differ considerably between wildlife and livestock species. While spatial and temporal patterns of WVCs and AVCs as a whole are relatively well-studied (e.g., Joyce and Mahoney 2001; Huijser et al. 2008; Sullivan 2011), these patterns remain poorly understood for DAVCs. Failing to account for any differences between WVCs and DAVCs could reduce the overall effectiveness of the mitigation strategies.

The state of Montana is a prime example of a region where more explicit consideration of DAVCs and how they may differ from WVCs could potentially yield benefits for motorist safety and natural resource management. Livestock grazing occurs on public and private lands across much of Montana, with at least three million cattle, horses, and sheep combined statewide (USDA-APHIS 2016; Sommer 2017)

and over three million animal unit months<sup>1</sup> of grazing on state and federal lands (USFS 2016; BLM 2018; Montana 2018). Rural roads with high-speed limits and without artificial lighting, traits that are associated with higher human-fatality risk from DAVCs (Langley et al. 2006), are common throughout the state. Montana is also home to several Native American communities, which may have a high prevalence of DAVC-caused injuries (Zaloshnja et al. 2003). We use a 10-year, statewide collision data set for Montana to explore AVC patterns at multiple spatial scales (county and road segment) and temporal scales (diel and seasonal) and determine whether these patterns exhibit differences between DAVCs and WVCs. We consider the implications of our findings for designing appropriate AVC mitigation strategies in Montana and other regions where DAVCs represent a significant safety risk.

## Methods

We obtained data recorded by Montana Highway Patrol (MHP) for AVCs along roads statewide from 2008 through 2017. Collisions resulting in injury or death of a person, or at least \$1000 of property damage, are required by state law to be reported to law enforcement (Montana Uniform Accident Reporting Act, Section 61-7-109). Thus, records were likely biased towards collisions with larger animals (e.g., wild or domestic ungulates) that tend to cause greater damage or injury. However, records were unlikely to be spatially biased because MHP responds to reported collisions regardless of their location. The data set included 25,476 AVC records, of which 1771 (7%) were DAVCs and 23,705 (93%) were WVCs. Each record included geographic coordinates, year, month, time of day, collision type (DAVC or WVC)<sup>2</sup>, road identifier, lighting conditions, road conditions, weather conditions, and crash severity information.

We examined differences in diel patterns between DAVCs and WVCs by calculating the proportion of records associated with each collision type that occurred during each hour of the day. We used polar histograms to graphically compare diel patterns for DAVCs and WVCs. Because diel patterns could differ by season, we also generated polar histograms for each of the four seasons

<sup>1</sup> An animal unit month is the amount of forage required by one “animal unit” (AU) for 1 month. An AU is defined as one 1000-lb mature cow, or the equivalent number of individuals of another domestic species in terms of grazing demand (e.g., 5 sheep or 0.8 horses).

<sup>2</sup> Although many states in the western U.S. have large populations of both domestic horses and wild or feral horses, horses in Montana are almost exclusively domestic animals and are classified as such in collision records.

separately. We used Mardia–Watson–Wheeler uniform scores tests (Mardia and Jupp 2000) implemented in the *circular* package (Lund and Agostinelli 2017) for R (R Development Core Team 2017) to test for differences between diel distributions of DAVCs and WVCs. We also determined the proportions of AVCs that occurred in daylight, darkness, dawn, or dusk conditions, as noted in collision records, and used a chi-squared test of independence to determine whether these proportions differed between DAVCs and WVCs.

To compare seasonal patterns, we calculated the proportion of records associated with each collision type that occurred during each month of the year. We used a polar histogram and uniform scores test to assess differences in seasonal distributions of DAVCs and WVCs. Because most ungulates in the mountainous environments of western Montana migrate seasonally between higher and lower elevation areas, while those in the plains environments of eastern Montana are often nonmigratory (Brazda 1953; Peek and Lovaas 1968; Montana 1999), we repeated this analysis separately for counties east and west of the Rocky Mountain Front to account for possible geographic variation in seasonal patterns.

We examined differences in spatial patterns of DAVCs and WVCs at multiple spatial scales. To determine how well regions of high risk for DAVCs and WVCs aligned at a coarse scale, we calculated and visually assessed three metrics at the county level: (1) the total number of WVCs in the county; (2) the total number of DAVCs in the county; and (3) the proportion of AVCs in the county that were DAVCs. We also conducted a statistical test of similarity between county-level DAVC and WVC spatial distributions using a nonparametric Monte Carlo approach that compares two point patterns and determines where one point pattern has a significantly greater concentration, a significantly lesser concentration, or exhibits no significant difference from another point pattern (Andresen 2009). This approach is applicable to cases in which two data sets with different numbers of points are being compared, such as our study in which >10 times as many WVCs as DAVCs were recorded.

Following Andresen (2009), we: (1) designated WVCs as the reference data set and calculated the proportion of statewide WVCs that occurred in each county; (2) designated DAVCs as the test data set and generated 1000 random samples, each consisting of 85% of the records in the test data set; (3) calculated the proportion of statewide DAVCs that occurred in each county for each random sample; (4) calculated a 95% confidence interval for each county from the proportion values for the 1000 random samples; and (5) assigned each county to one of three categories (WVC > DAVC, no significant difference, or DAVC > WVC) by comparing the county proportion values

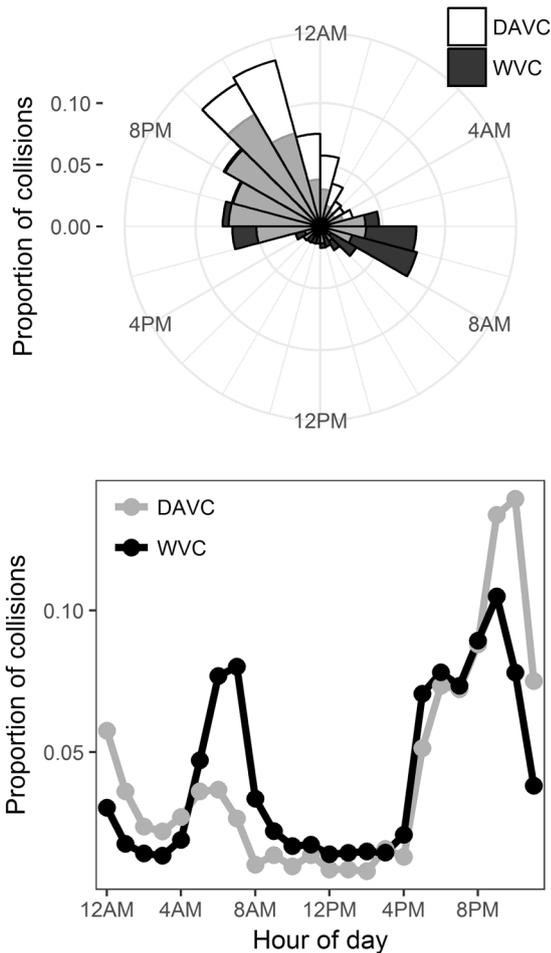
from the reference data set to the 95% confidence intervals from the test data set.

We explored overlap among DAVC and WVC hotspots at a finer spatial scale within one county with a relatively low proportion of DAVCs (Flathead County) and one county with a relatively high proportion of DAVCs (Glacier County). We used a kernel-smoothed point intensity function implemented in the *spatstat* package (Baddeley et al. 2015) for R to visually compare hotspots for DAVCs and WVCs in each county. We then repeated the nonparametric similarity test described above, but used 1-mile (1.6-km) road segments rather than counties as the spatial unit of analysis, to determine whether DAVCs and WVCs tended to be clustered along similar road stretches within each county. All statistical analyses were performed in R version 3.4.3.

Finally, we examined trends in annual DAVC and WVC numbers to determine if these types of collisions have become more or less frequent over the last decade. We visually compared these temporal trends for AVCs to trends for (1) statewide numbers of livestock (including cattle and sheep) and wild ungulates (including mule deer, whitetail deer, elk, and pronghorn [*Antilocapra americana*]), and (2) statewide traffic volumes measured as annual vehicle miles traveled, to assess whether changes in AVC numbers were consistent with changes in these factors. We limited our comparisons to the 2011–2017 period during which data for all factors of interest were available. Livestock numbers were obtained from annual statistical bulletins produced by the USDA's National Agricultural Statistics Service ([https://www.nass.usda.gov/Statistics\\_by\\_State/Montana/Publications/Annual\\_Statistical\\_Bulletin/](https://www.nass.usda.gov/Statistics_by_State/Montana/Publications/Annual_Statistical_Bulletin/)). Wildlife population estimates were obtained from Montana Department of Fish, Wildlife, and Parks annual population status reports (<http://fwp.mt.gov/fishAndWildlife/management/>). Traffic volume estimates were obtained from Montana Department of Transportation ([https://www.mdt.mt.gov/other/webdata/external/Planning/traffic\\_reports/tbcounties.pdf](https://www.mdt.mt.gov/other/webdata/external/Planning/traffic_reports/tbcounties.pdf)).

## Results

Diel distributions differed between DAVCs and WVCs ( $W = 264$ , d.f. = 2,  $p < 0.001$ ). WVCs exhibited two clear peak periods: a morning peak from ~5 a.m. to 8 a.m., and an evening peak of slightly greater magnitude from ~5 p.m. to 11 p.m. (Fig. 1). In contrast, DAVCs exhibited only one extended peak period from ~5 p.m. to 1 a.m., with an especially large proportion of collisions occurring between 9 p.m. and 11 p.m. DAVCs also showed a minor morning peak period between 5 a.m. and 8 a.m., but of very small magnitude compared with WVCs. Although there were some variations among seasons with respect to the timing of

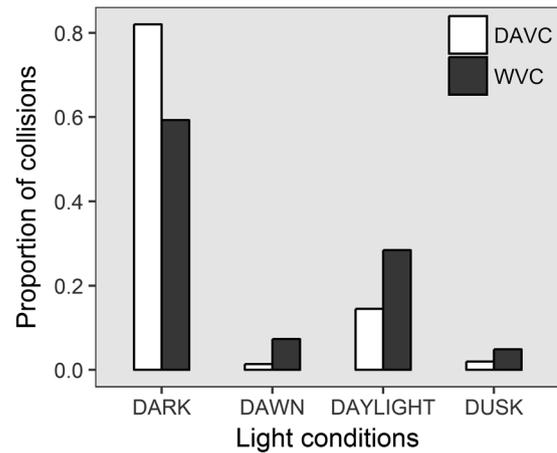


**Fig. 1** Proportions of domestic animal-vehicle collisions (DAVCs) and wildlife-vehicle collisions (WVCs) occurring during each hour of the day in Montana from 2008 through 2017. Top panel: results displayed as a circular histogram, in which the length of each bar is proportional to the fraction of DAVCs or WVCs occurring in a given hour period; gray portions of bars represent overlap between the two collision types. Bottom panel: results displayed as a line graph

morning and evening peaks, presumably due to seasonal shifts in timing of sunrise and sunset, the general patterns described above were observed in all seasons (Fig. A1).

WVCs and DAVCs also differed with respect to light conditions at the time of collision ( $\chi^2 = 368.42$ , d.f. = 3,  $p < 0.001$ ). The majority of collisions occurred in dark conditions for both DAVCs and WVCs; however, relatively speaking, WVCs were more likely during dusk, daylight, and dawn conditions, while DAVCs were more likely during dark conditions (Fig. 2).

Seasonal patterns differed between DAVCs and WVCs ( $W = 38.643$ , d.f. = 2,  $p < 0.001$ ). Both collision types were least common during winter and early spring, and most common during summer and fall months (Fig. 3). However, DAVCs exhibited a more prominent peak from September through November, while the summer/fall peak for WVCs

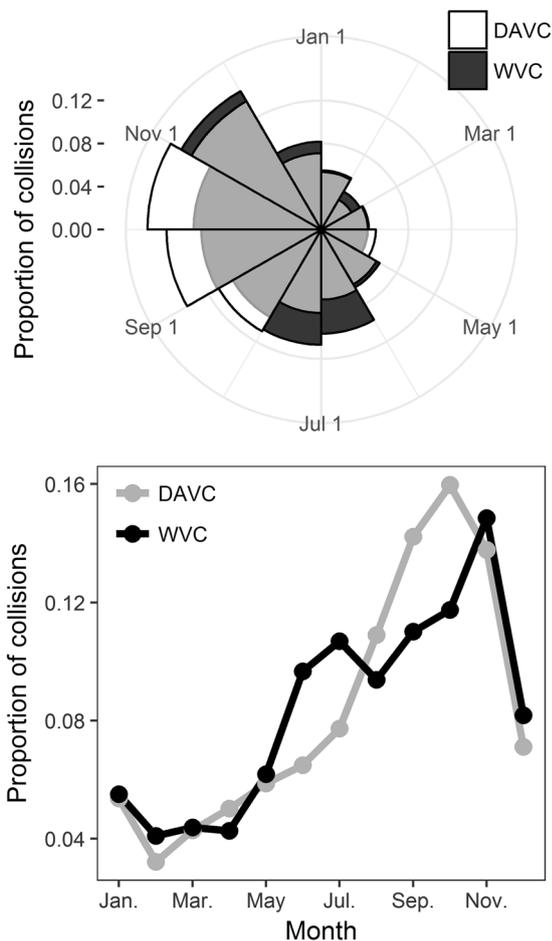


**Fig. 2** Proportions of domestic animal-vehicle collisions (DAVCs) and wildlife-vehicle collisions (WVCs) occurring under different light conditions in Montana from 2008 through 2017

was more evenly distributed from June through November. Seasonal patterns were very similar for counties in eastern and western Montana (Fig. A3).

At both coarse and fine scales, we found that areas where WVCs were most likely to occur were not spatially consistent with areas where DAVCs were most likely to occur. We observed large variation among counties with respect to the number of WVCs (range: 7–2278; Fig. 4a), the number of DAVCs (range: 1–180; Fig. 4b), and the proportion of AVCs that were DAVCs (range: 0.015–0.489; Fig. 4c). The highest numbers of WVCs were recorded in western Montana (i.e., west of the Rocky Mountain Front), particularly in northwest Montana. DAVC numbers were more evenly distributed across the state, although Glacier County in northern Montana was a clear outlier with a very large number of DAVCs relative to its size. DAVCs tended to make up a greater proportion of all AVCs in eastern Montana counties, where total AVC numbers were typically lower. Our statistical test of county-level similarity showed that at a coarse spatial scale, WVC and DAVC spatial patterns were significantly different across the majority of the state (48 of 56 counties; Fig. 4d). DAVCs were significantly overrepresented relative to WVCs in most eastern Montana counties, while the opposite was true in most western Montana counties.

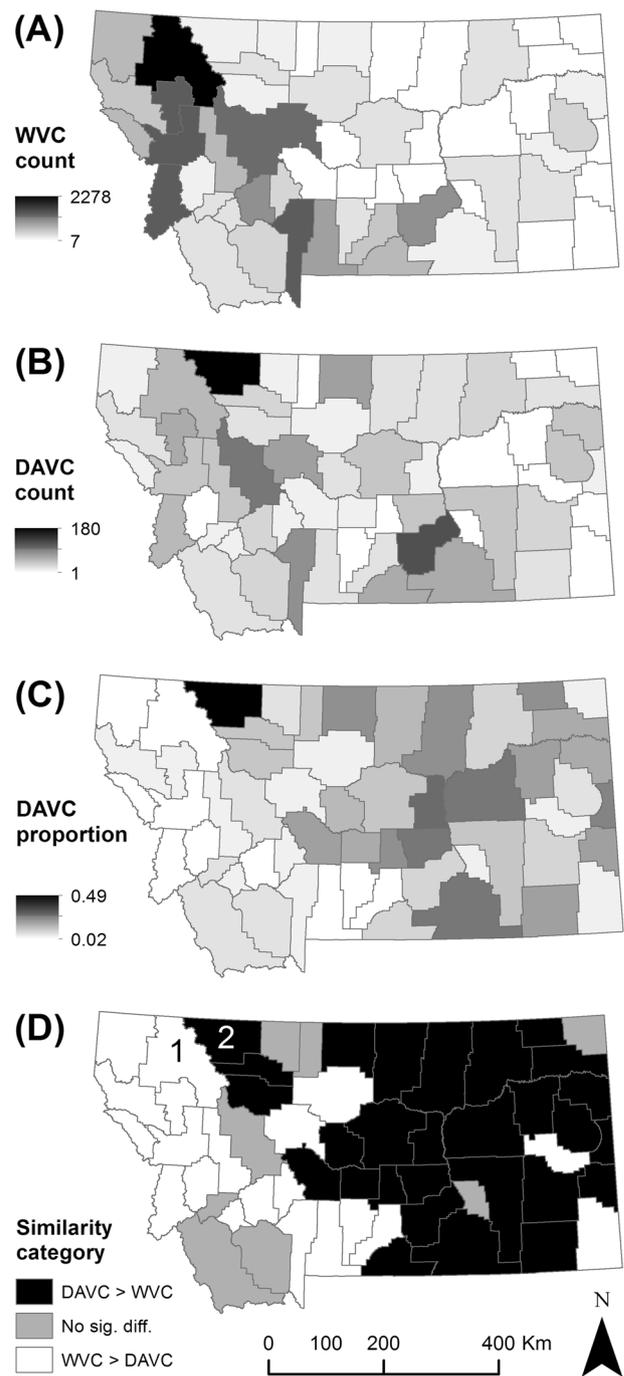
We found further evidence for spatially inconsistent WVC and DAVC hotspots at the 1-mile road segment scale within both Flathead County, which has a low proportion of DAVCs, and Glacier County, which has a high proportion of DAVCs (Fig. 5). Maps of kernel-smoothed point intensity showed that while road segments with both high WVC and high DAVC concentration (or low WVC and low DAVC concentration) existed in both counties, many of the most prominent hotspots of each collision type did not overlap. Approximately 62 and 33% of the



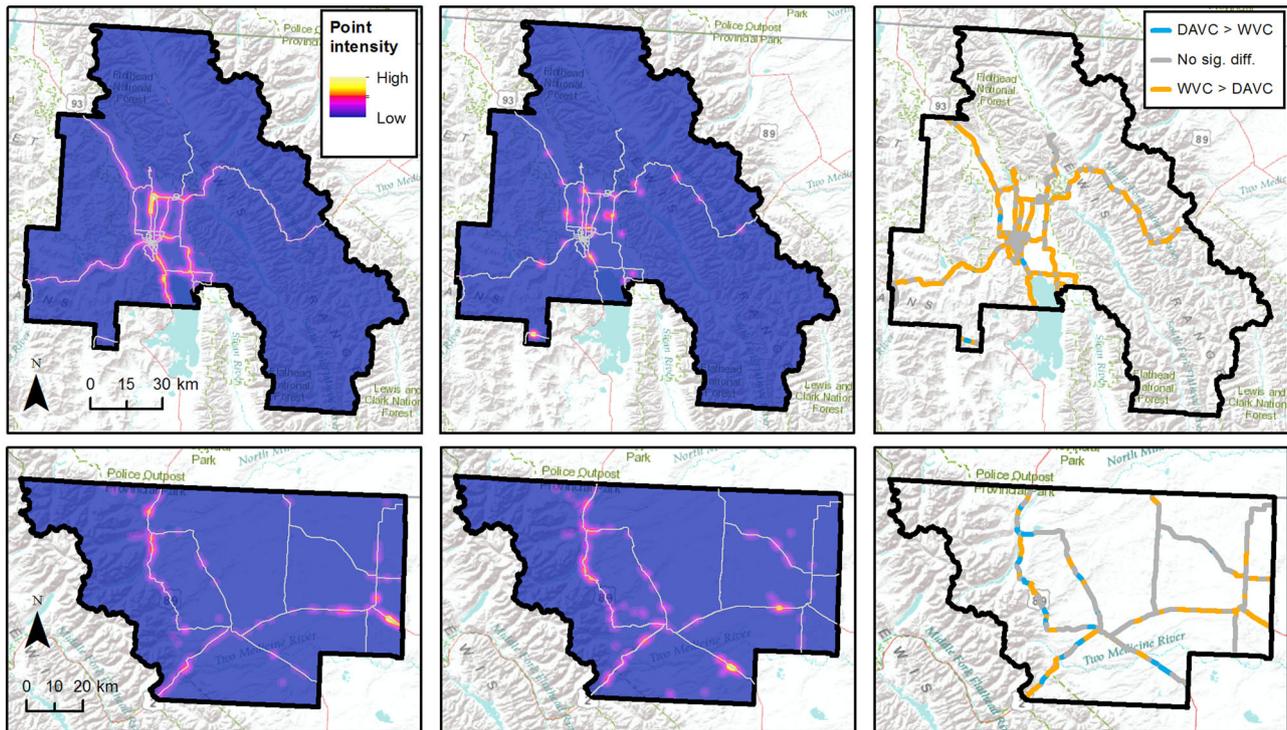
**Fig. 3** Proportion of domestic animal-vehicle collisions (DAVCs) and wildlife-vehicle collisions (WVCs) occurring in each month of the year in Montana from 2008 through 2017. Top panel: results displayed as a circular histogram, in which the length of each bar is proportional to the fraction of DAVCs or WVCs occurring in a given month; gray portions of bars represent overlap between the two collision types. Bottom panel: results displayed as a line graph

1-mile segments in Flathead and Glacier counties, respectively, exhibited point patterns for WVCs and DAVCs that were significantly different according to our similarity test.

Our examination of statewide annual trends revealed that DAVC counts were relatively stable over time (6.3% decrease between 2011 and 2017), whereas WVC counts increased dramatically during this period (79.9% increase; Fig. 6). The observed trends in DAVCs and WVCs were mirrored by trends in livestock and wild ungulate populations, respectively. Cattle and sheep populations were relatively constant through time, while wild ungulate populations increased by 40.1% collectively, with increases ranging from 16.4 to 74.8% for individual ungulate species. Annual vehicle miles traveled exhibited a modest increase of 8.4% from 2011 to 2017 (Fig. 6).



**Fig. 4** County-level comparisons of spatial distributions of domestic animal-vehicle collisions (DAVCs) and wildlife-vehicle collisions (WVCs) in Montana from 2008 through 2017. **a** Total number of WVCs observed in each county. **b** Total number of DAVCs observed in each county. **c** Proportion of AVCs in each county that were DAVCs; counties labeled 1 and 2 (Flathead and Glacier counties, respectively) were selected for finer-scale spatial comparison of DAVC and WVC hotspots. **d** Categorical output of nonparametric statistical test indicating whether DAVCs were overrepresented relative to WVCs (black polygons), WVCs were overrepresented relative to DAVCs (white polygons), or there was no statistically significant difference in spatial patterns of DAVCs and WVCs (gray polygons)



**Fig. 5** Comparison of domestic animal-vehicle collision (DAVC) and wildlife-vehicle collision (WVC) hotspots for two Montana counties—Flathead County (top row) and Glacier County (bottom row)—from 2008 through 2017. Left and middle columns show kernel-smoothed

point intensity estimates for WVCs and DAVCs, respectively. Right column shows results of nonparametric test for similarity of WVC and DAVC point patterns within each 1-mile segment along major routes within the county

## Discussion

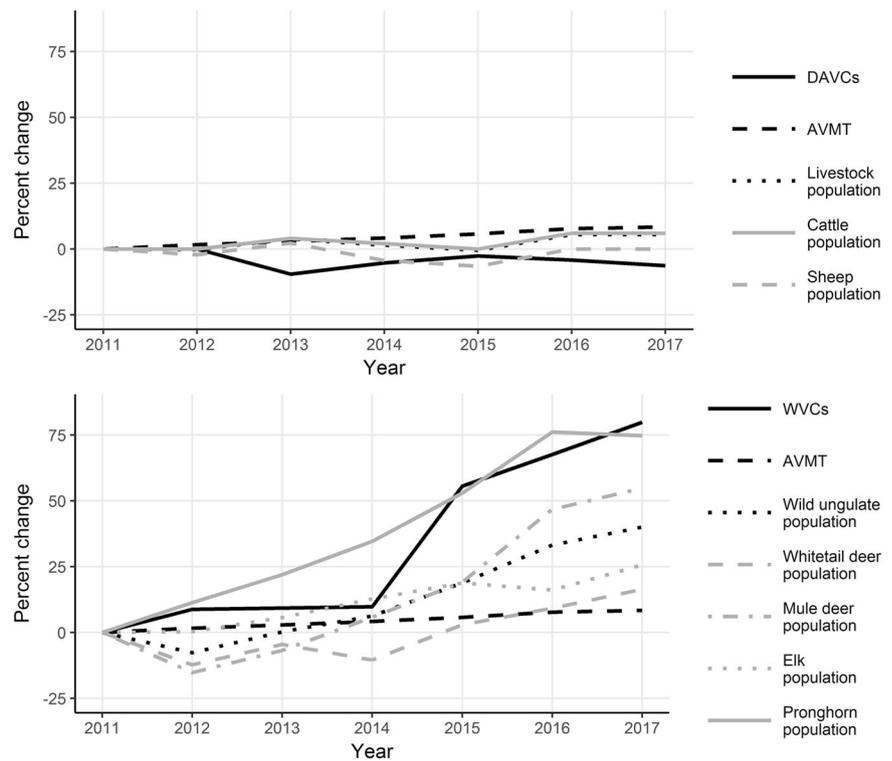
Vehicle collisions with domestic animals have largely been ignored by researchers or subsumed within broader studies of AVCs, likely because they account for a minority of AVCs in other regions (i.e., <15% in California and Utah; Perrin and Disegni 2003; Huijser et al. 2008). Our results from Montana indicate that DAVCs comprise 7% of AVCs in Montana but differ from more commonly studied WVCs with respect to the time of day, time of year, and location in which they occur. Understanding the spatial and temporal patterns of each type of AVC is necessary to facilitate more effective mitigation strategies that account for these differences.

The diel pattern of dawn and dusk peaks that we observed for WVCs is consistent with studies from other regions (Haikonen and Summala 2001; Sullivan 2011; Lagos et al. 2012; Steiner et al. 2014). This pattern is likely driven by a combination of factors, including (1) ungulates are most active around dawn and dusk (Georgii 1981; Beier and McCullough 1990; Green and Bear 1990); (2) traffic volumes are relatively high around dawn and dusk, which roughly correspond with morning and evening commuting periods in suburban and urban areas (Hallenbeck et al. 1997; Kim et al. 2008); and (3) low light conditions make it

more difficult for drivers to spot hazards, such as large animals, and react appropriately (Lamm et al. 1985; Wanvik 2009; Al-Dulaimi 2015). The contrasting pattern for DAVCs that we observed—with only one major peak centered on the 9 p.m. to 11 p.m. period—has not been previously documented to our knowledge and is more difficult to explain. Information on diel activity patterns of domestic livestock is scarce but suggests that livestock are primarily diurnal (Arnold and Dudzinski 1978; Van Rees and Hutson 1983; Stott et al. 2018), making activity level an unlikely explanation for the observed late evening peak. The most plausible explanation in our opinion is related to both light conditions and traffic volumes: livestock are the most vulnerable to collisions during late evening because it is dark and animals are less visible to motorists, but a substantial number of vehicles remain on the road. This explanation would account for low DAVC rates during daylight periods and during periods when it is dark but traffic volumes are low (i.e., between 1 a.m. and 5 a.m.), although further investigation is needed.

The seasonal pattern of WVCs that we observed is also consistent with previous research (Langley et al. 2006; Huijser et al. 2008; Sullivan 2011) showing low WVC frequencies from winter through early spring and elevated frequencies from late spring through fall, peaking in

**Fig. 6** Statewide trends in annual animal-vehicle collision counts, animal population sizes, and annual vehicle miles traveled (AVMT) from 2011 through 2017 in Montana. Top panel: domestic animal-vehicle collisions and domestic animal population sizes; “livestock population” is the sum of cattle and domestic sheep population sizes. Bottom panel: wildlife-vehicle collisions and wildlife population sizes; “wild ungulate population” is the sum of whitetail deer, mule deer, elk, and pronghorn population sizes. Percent change is calculated using 2011 values as a baseline



November. This fall peak has been attributed to increased ungulate activity level associated with migration and breeding behavior, which brings ungulates in contact with the road network more frequently (Green and Bear 1990; Ager et al. 2003). Interestingly, we found little difference in seasonal WVC patterns between western Montana counties where ungulates tend to exhibit migratory behavior and eastern counties where migratory behavior is less common (Fig. A3), which suggests that factors other than migration are responsible for this pattern (e.g., increased activity rates and road crossings by ungulates during the rut). The slightly different seasonal pattern for DAVCs, which exhibited a stronger peak in September through November, has not been documented elsewhere to our knowledge. In western Montana, this fall DAVC peak may coincide with movement of livestock from high-elevation summer grazing areas to valley-bottom ranches prior to winter; however, the similar pattern we observed for eastern Montana, where elevation is much less variable, again suggests that other factors are likely important.

We observed differences between DAVC and WVC hotspots at both coarse (county-level) and fine (1-mile road segment) spatial scales, a finding that has major implications for how AVC risk can best be managed within Montana. Perhaps the most striking pattern was an east-west divide with respect to the relative proportions of WVCs and DAVCs by county, with DAVCs generally comprising larger fractions of AVCs in eastern counties. We suspect

that this pattern is driven by broad-scale differences in the relative densities of wild ungulates and livestock across the state, with livestock comprising a greater fraction of the total population of large animals in eastern than western counties. However, we lack county-level wildlife density data needed to directly test this hypothesis and cannot rule out other factors. Unlike the proportions of DAVCs, raw counts of DAVCs were more evenly spread across the state and may reflect a balance between traffic volumes (higher in many western counties) and livestock numbers (higher in eastern counties). A simple post hoc regression analysis indicated that DAVC counts are better predicted by traffic volumes ( $R^2 = 0.30$ ; Fig. A4) than by livestock population sizes ( $R^2 = 0.05$ ; Fig. A5) at the county level.

Differences in locations of DAVC and WVC hotspots at the local scale likely result from a combination of factors. The presence and type of highway fencing may be important, as wildlife-friendly fence designs typically allow wildlife to access and cross roadways but exclude most livestock (Paige 2008); breaches in fencing may therefore funnel livestock, but not wildlife, onto roadways at particular locations. The spatial distribution of pastures and rangelands, including their adjacency to roads, may further explain local DAVC hotspot locations. WVC hotspot locations may be driven by environmental features that facilitate movement (e.g., riparian corridors) or serve as attractants (e.g., agricultural crops utilized by ungulates). More detailed investigation of factors associated with hotspots of WVCs

and DAVCs, especially the latter, is needed to fully understand why these differ at fine spatial scales.

Our results highlight that DAVCs can be locally common even when regionally rare, and thus they may represent a high priority for management and mitigation measures to protect human safety in some areas. The most conspicuous example from our study was the Blackfoot Indian Reservation in northern Montana, where 59% of recorded AVCs involved domestic animals. More generally, DAVCs appear to occur disproportionately on reservation lands statewide: 22% of statewide DAVCs in our analysis occurred on reservation lands, which account for <10% of the state's area and major road network. DAVCs also tended to be over-represented relative to WVCs on reservation lands, with DAVCs accounting for 19% of AVCs on reservation lands but only 6% on non-reservation lands. The causes and consequences of elevated DAVC risk on reservation lands warrant further attention; potential explanations could include absence or poor maintenance of roadside fencing, limited law enforcement response to livestock on roads, and lack of legal liability for ranchers whose livestock are involved in DAVCs. Encouragingly, there is evidence that mitigation measures, such as livestock control programs, can reduce risks to human safety while generating net economic savings for tribal communities (Zaloshnja et al. 2003).

The case for increased consideration of DAVCs is further strengthened by the fact that although they are rarer than WVCs, DAVCs are more dangerous to motorists on a per-collision basis. Our analysis for Montana found that a DAVC was three times as likely as a WVC to result in a fatality and 1.5 times as likely to result in an incapacitating injury (Fig. A2). Studies of AVCs in Utah, Nevada, and Texas have also found that DAVCs are more likely to result in human injury or death (Wildlife Quality Improvement Team 2005; Burton et al. 2014; Cramer and McGinty 2018). Thus, observed counts of AVCs may not accurately reflect the overall risk to human safety if DAVCs and WVCs are not differentiated. This differentiation is especially consequential for the allocation of state and federal transportation agency safety funding because priority locations for mitigation measures are typically established on the basis of economic costs of collisions, which are estimated to be several orders of magnitude higher for human-fatality accidents than property-damage-only accidents (Huijser et al. 2009).

Although they present a serious safety risk, DAVCs do not appear to be increasing in frequency in Montana, and in fact represent a declining fraction of AVCs statewide because WVCs have increased considerably in recent years (Fig. 6). This trend is likely related to variation in the size of livestock and wild ungulate populations through time: WVCs have increased approximately in tandem with the combined number of deer, elk, and pronghorn in Montana since 2011, while both DAVCs and livestock numbers have

remained relatively flat. Increases in statewide traffic volumes, although relatively modest, could also be contributing to the overall increase in AVCs.

Mitigation measures that address collisions with domestic animals may be different than those for wildlife. For example, putting reflective material on domestic animals has been attempted for reindeer in Finland (Huuhtanen 2016) and camels in Oman (Abu Abdo and Al-Ojaili 2015), although neither method has proven effective. Reflective livestock ear tags and ankle wraps are commercially available in the United States for cattle, horses, and other livestock, but we are unaware of any empirical evidence for their effectiveness at reducing DAVCs. Another mitigation measure that may prove effective is the lighting of problematic highway segments with high rates of DAVCs. Highway lighting gives drivers more time to react to an animal on the road, and because DAVC rates in Montana are highest during periods of darkness, this may be a potential solution. Other mitigation measures that have proven effective and are used primarily to address WVCs, such as animal detection-driver warning systems and wildlife overpasses and underpasses with wildlife exclusionary fencing, could also be deployed to address DAVCs, particularly where the two coincide. Wing-fencing added to existing below-grade bridge passages such as bridge structures and prefabricated concrete culverts could be a relatively low-cost mitigation investment.

DAVCs and WVCs also differ with respect to laws governing potential liability for damage. Because the law typically defines domestic animals as personal or private property (e.g., MONT. CODE ANN. § 15-1-101 [2017]), owners may incur liability as a result of a motorist striking their livestock on a public roadway (*Larson-Murphy v. Steiner*, 303 Mont. 96, ¶ 89 [2000]). The extent of legal vulnerability may be influenced by whether a DAVC occurs within an “open range” or “closed range” area (Archer 2002). Property owners are responsible for “fencing out” neighbors' unwelcome animals in open range areas, while livestock owners are responsible for “fencing in” their livestock in closed range areas (*Larson-Murphy* ¶¶ 46–48). Outside of incorporated cities and towns, most of Montana is legally classified as open range (Mosley 2011).

Livestock owners in Montana open range are neither required to keep their livestock off the highway nor responsible for damages from DAVCs involving their livestock, except in cases of gross negligence or intentional misconduct (MONT. CODE ANN. § 27-1-724 [2001]).<sup>3</sup> However, such laws vary among western states; for instance, Arizona and Colorado impose a duty of reasonable care on

<sup>3</sup> Certain exceptions exist for state highways that are part of the national system of interstate and defense highways or part of the federal-aid primary system (MONT. CODE ANN. § 27-1-724 [2001]).

livestock owners (*Millard v. Smith*, 495 P.2d 234, 235 [Colo. 1972]; *Carrow v. Lusby*, 804 P.2d 747, 754 [Ariz. 1990]), while Idaho and Nevada provide complete immunity for owners of livestock involved in collisions in open range areas (Idaho Code § 25-2118 [2018]; NEV. REV. STAT. § 568.360). Thus, reducing DAVCs would benefit livestock owners not only by decreasing economic losses associated with livestock mortality, but also by lowering their risk of liability in some states.

Future research should include collection of detailed information not only on the location and timing of collisions with wild and domestic animals, but also on the species of animals killed in collisions. Previous WVC studies have demonstrated that collision hotspots for different wildlife species are not necessarily coincident, particularly at finer spatial scales (Teixeira et al. 2013; McClure and Ament 2014), and that optimal mitigation measures differ among species (van der Grift et al. 2013). These insights have led to more informed and effective strategies for minimizing WVCs (McClure and Ament 2014; Teixeira et al. 2017; Zeller et al. 2018; Find'o et al. 2019), and applying these species-level distinctions to collisions with domestic animals could lead to similar progress in mitigating DAVC risk while requiring very little extra data collection effort.

WVC studies rely on a variety of data sources other than collision records—including telemetry data, track surveys, genetic sampling, camera trapping, GIS- or expert-based movement models, local knowledge, and information on compatibility of surrounding land use—to design effective mitigation strategies (Clevenger and Huijser 2011). A similarly comprehensive approach could be used to design more effective mitigation strategies for DAVCs by incorporating information on local grazing laws (open range versus herd district), status of roadside fencing, local livestock densities, proximity of public grazing allotments or private pasture to roads, and traditional routes used by livestock moving between home ranches and seasonal grazing locations. Such an approach could allow us to move from simply documenting DAVCs to anticipating and preventing DAVCs using ancillary data.

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## Compliance with Ethical Standards

**Conflict of Interest** The authors declare that they have no conflict of interest.

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