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Urban Alaskan Moose: An Analysis of Factors Associated with Moose-Vehicle Collisions

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URBAN ALASKAN MOOSE: AN ANALYSIS OF FACTORS ASSOCIATED WITH

MOOSE-VEHICLE COLLISIONS

by

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ABSTRACT

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As human populations continue to grow and encroach into wildlife habitats, instances of human-wildlife conflict are on the rise. Increasing numbers of reported wildlife-vehicle collisions (WVCs) provide tangible evidence of anthropogenic impacts on wildlife as well as increasing threats to human health and safety. Within the four most populated boroughs of Alaska, moose-vehicle collisions (*Alces alces*; MVCs) are common, but the risk is disproportionate to human population size. I analyzed historical records of MVCs across the state between 2000 and 2012 to compare daily and annual trends in MVC risk to the expected behavioral patterns of moose and humans. Across the state, the distribution of MVCs was skewed towards winter and towards hours of the day with less visibility. Fifty percent of reported MVCs occurred where the commuter rush hours overlapped with the dusk and dawn in winter, when moose are expected to be most active. I observed a less pronounced peak in winter MVCs in areas where light pollution along the road system was higher.

To understand factors of MVC risk at a finer scale, I collected vegetation and road geometry data at 400 reported MVC locations across the Matanuska-Susitna Borough of Alaska between 2016 and 2018. I used this data, along with spatially extracted data, to construct generalized additive mixed models of MVC risk. Similar spatially extracted data was collected for 2,772 sites where radio-marked moose within the study area crossed roads to build a comparative model of moose road crossing risk. The final model of MVC risk included predicted snow presence, solar altitude, road sinuosity, area of the roadside obstructed by vegetation, and the angle between the road and the roadside (R^2 = 38.7%). The final model of moose crossing risk included the spatial coordinates, predicted snow presence, solar altitude, traffic volume, road density, distance to nearest building, light reflectance, land cover interspersion, and proportions of deciduous-coniferous and coniferous forest (R^2 = 49.3%). To understand the effect of each factor in these models, I manipulated each to its observed maximum or minimum and used the original model to predict MVC risk again. Winding roads, which would allow for high visibility but likely induce lower speeds, reduced MVC risk by 35.8%, and minimizing roadside vegetation reduced MVC risk by 14.6%. Extremely high light reflectance reduced moose crossing risk by 55.2%. Overall, recommended mitigation efforts include seasonal lighting or reduced speeds in areas heavily impacted by MVCs, roadside vegetation clearing, and centralization of future urban planning to areas that are already heavily urban.

(93 pages)

PUBLIC ABSTRACT

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As human populations continue to grow and encroach into wildlife habitats, instances of human-wildlife conflict are on the rise. Increasing numbers of reported wildlife-vehicle collisions (WVCs) provide tangible evidence of anthropogenic impacts on wildlife as well as increasing threats to human health and safety. Increasing WVCs are of particular concern, especially those involving large-bodied ungulates such as moose (Alces spp.), because of the increased risk of property damage, personal injuries, and human fatalities. Motorists directly involved in a WVC are at risk of injury or mortality, but other motorists are also put at risk due to road obstructions and traffic congestion associated with WVCs. Mitigating these impacts on motorists and wildlife requires investigation into the temporal and spatial factors leading to WVCs.

In Alaska, most WVCs involve moose (Alces alces), a large bodied ungulate capable of threatening human life when involved in a collision. Each moose-vehicle collision (MVC) in Alaska is estimated to cost $33,000 in damages. With this analysis, I analyzed the plethora of factors contributing to moose and motorist occurrence on the road system and motorist detection based on a historical dataset of MVC reports throughout Alaska from 2000 to 2012 and a dataset of field-derived measurements at MVC locations within the Matanuska-Susitna Borough from 2016 to 2018. My first analysis focused on the daily and annual trends in MVC rates as compared to expected

moose and human behavioral patterns with a focus on guiding mitigation strategies. Fifty percent of the MVCs reported between 2000 and 2012 occurred where the commuter rush hours overlapped with dusk and dawn in winter, and the artificial lighting differences between boroughs suggest a link between artificial lighting and reduced MVCs.

To focus more specifically on roadside features contributing to MVC risk, I collected and analyzed local and regional scale land cover and road geometry data at reported MVC sites in an area with a rapidly growing human population. I compared these data to similar data collected at random locations near documented MVC sites and at locations where moose that were fitted with global-positioning system (GPS) transmitters crossed highways. I used generalized additive mixed models to delineate which of the variables impacted the risk of both moose road crossings and MVCs. Moose road crossings were influenced by approximations of spatial, seasonal, and daily moose density as well as the proportion of deciduous-coniferous and coniferous forest in the area and the number of possible corridor or land cover types surrounding the site. The best MVC risk model was described by expected seasonal and daily changes in moose density and local scale measurements, including the sinuosity of the road, the height of vegetation near the road, and the angle between the road surface and the roadside. Together this information should guide transportation and urban planners in the Matanuska-Susitna Borough to use roadside vegetation removal, seasonal speed reduction, improved lighting strategies, dynamic signage, or partnerships with mobile mapping services to reactively reduce MVCs and to focus future road planning in areas with lower moose abundance and build roads that increase visibility and detection distances in areas where moose are common.

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Lucian R. McDonald

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

“Human-wildlife conflict” is a phrase often used to describe negative interactions between humans and wildlife (Messmer 2000). As humans have increased their use of space and resources, negative interactions with wildlife have increased. Human-wildlife conflicts often occur when wildlife harm, or are thought to harm, a human or their property, crops, or livestock (Conover et al. 1995, Messmer 2000, Treves et al. 2006, Dickman 2010). Human-wildlife conflicts can lead to negative public opinion regarding the involved species, destruction of the involved individual, and/or negative socio-economic impacts for the humans involved (Conover et al. 1995, Dickman 2010, Barua et al. 2013, Khumalo and Yung 2015). In areas where urbanization and human population growth are increasing, documenting and responding to human-wildlife conflicts with proactive mitigation efforts may keep public opinion of the species involved positive overall (Kilpatrick and LaBonte 2003, Siemer et al. 2013).

As a consequence of increased urbanization and human population growth, the extent of road systems, and their associated speed and traffic volumes, have increased, which has led to increased wildlife-vehicle collisions (WVCs; Conover et al. 1995, Grilo et al. 2009, Morelle et al. 2013, Brieger et al. 2017). Due to these increased traffic volumes and speeds, modern WVCs are more dangerous for both the motorist and the wildlife involved, especially when that wildlife is a large-bodied ungulate (Niemi et al. 2017). In fact, research in Scandinavia found that accident severity was higher during summer, spring, and autumn when WVCs were less likely to occur, and they attributed

this phenomenon to better driving conditions and higher summer speed limits (Niemi et al. 2017).

To fully understand human-wildlife conflicts such as WVCs, one needs to know the humans involved, the wildlife involved, and the environmental conditions that led to the incident (Decker et al. 2012). More specifically, WVCs arise due to three interacting probabilities: 1) that an animal is crossing a road at a particular time and location, 2) that a motorist is bisecting this same location at the same time, and 3) that this motorist's detection and reaction time is hindered (Forman et al. 2003, Seiler 2005, Chen and Wu 2014). Based on animal and human behavior, researchers have modeled these probabilities to predict when and where management efforts are most needed (Forman et al. 2003, Coffin 2007, Gunson et al. 2011, Steiner et al. 2014). Depending upon data availability, these models include varying degrees of spatial or temporal extent from spatial coordinate level data to aggregated county or statewide data that cover either specific seasonal periods or year-round longitudinal studies.

WVCs are typically reported to local law enforcement to ensure coverage of damage by the motorist's auto insurance provider, but the reporting rate can depend upon the amount of damage involved (Snow et al. 2015). With these WVC reports, researchers are able to locate these WVCs and measure variables specific to their occurrence throughout the year. In Alaska, the most common species involved in WVCs is moose (*Alces alces*). Based on past studies, we know that moose-vehicle collisions (MVCs) in Alaska are clustered in winter (Del Frate and Spraker 1991). We expect this seasonal surge in MVCs is due to three factors: 1) decreased ability to detect moose as days grow shorter and weather conditions worsen, 2) use of roads by moose as snow-free travel

corridors, and 3) increased moose density due to seasonal constriction of home ranges to lower elevation areas (Del Frate and Spraker 1991, Gunson et al. 2011, Steiner et al. 2014).

Decreased motorist detection during winter is often cited in studies of MVC risk, but in Alaska, the difference between summer and winter visibility is much more drastic. Depending upon latitude, ambient light at each solstice can be present all day in summer or for an hour or less during winter, which can impact both human and moose activity (Steiner et al. 2014). Weather conditions further impact both motorist detection and moose activity. Winter in Alaska is usually characterized by snowy conditions that can decrease motorist detection and simultaneously drive moose into valleys where snow depths are lower or directly onto roads for a less resistant travel path (Del Frate and Spraker 1991, Rolandsen et al. 2011, Krauze-Gryz et al. 2017).

Our current assumptions of seasonal moose space use are based on the work of Ballard and Whitman (1988), which defines the expected seasonal movement behavior of moose in south-central Alaska (Pritchard et al. 2013). Moose are expected to inhabit two seasonal home ranges, one at low elevation during winter and one at higher elevation during summer, and exhibit two migration periods in spring and fall. Due to the lack of predators, non-seasonal forage availability, or other human-derived factors, moose living in close proximity to humans may be less likely to exhibit such space-use patterns, choosing instead to live year-round in their low-lying human-populated winter ranges (Finder et al. 1999, McCance et al. 2015).

Occurrence of humans on the road system is usually well defined by transportation agencies or easily extrapolated based on the complexity of the road itself,

such as the width and number of lanes; however, the occurrence of moose can be difficult to predict due to their generalist diet and, in the case of our study area, relatively high abundance on the landscape. Attractants bringing moose to an area may include the specific vegetation along the roadside, larger scale habitat composition metrics or landscape features, or the presence of travel corridors (Finder et al. 1999, Chen and Wu 2014, Clevenger et al. 2015, Bartonicka et al. 2018). Alternatively, moose may be deterred from areas where human disturbance is higher, such as near highly trafficked roads or in areas of high hunting pressure (Seiler 2005). Hunting pressure has also been suggested as a cause of WVCs, due to increased movement of animals when hunters are present, but research has shown moose movement rates during hunting seasons are lower than in other times of the year (Neumann et al. 2009, Lagos et al. 2012).

Based on personal experience as well as video evidence, moose behavior when confronted by a vehicle is typically either to not respond or to flee in the direction the car is heading, putting the onus of preventing an MVC directly in the hands of the motorist (Rea et al 2010, Rea et al. 2018). This can lead to deadly consequences for impaired or distracted motorists, but data to separate these motorists from those who simply could not see the animal are difficult to obtain. Most modeling attempts have left this as a random effect, and without surveying each motorist involved in MVCs, this may remain unmeasurable. Based on the Alaska Department of Transportation and Public Facilities database of compiled traffic reports between 2000 and 2012 and the moose specimens returned to the Alaska Department of Fish and Game between 2015 and 2018, we do know that the majority of motorists involved in MVCs were male (64.7% of reports where gender is listed) and had ages equally distributed among the driving age

population, and the majority of moose involved in MVCs were female (64.6%) and were calves (41.2%), yearlings (16.0%), or two years old (12.7%).

Causes of visual impairment, in regard to motorist detection, are often measured and implemented in WVC modeling attempts (Haikonen and Summala 2001, Dussault et al. 2006, Ramp et al. 2006). The height and type of vegetation along the roadway, while measured to account for motorist visibility or moose attraction, can also lead to changes in motorist behavior (Finder et al. 1999, Antonsen et al. 2015). When vegetation is low and the field of view is open, motorists have been found to drive faster and closer to the roadside (Antonsen et al. 2009). This leads to interacting effects between visibility and speed, which are inherently interrelated because higher speeds also lead to a longer stopping distance between what can be seen ahead and the vehicle itself (Rodgers and Robins 2006, Mastro et al. 2010). Studies have also accounted for objects along the roadway that are intended to help increase visibility, such as reflectors and signage (Sullivan et al. 2004, Mastro et al. 2010, Rytwinski et al. 2017). There are, however, mixed reviews from older studies when documenting the effect of artificial lighting structures for reducing WVCs (Reed and Woodard 1981, McDonald 1991). Newer information suggests wildlife avoid artificially lit areas, but the same interacting effects between visibility and speed mentioned previously may counteract this impact (Beyer and Ker 2009, Gaston et al. 2014). Furthermore, in highly trafficked areas the artificial light from oncoming traffic may cause decreased visibility, but accounting for such an effect is difficult. Overall, the time of day and time of year can heavily influence visibility, as well as animal mobility, especially in areas near the poles where sunrise and sunset are not as static year round and where snow accumulation can influence animal

behavior (Becker and Grauvogel 1991, Dussault et al. 2006, Steiner et al. 2014).

Methods for predicting the impact of each of these factors range from county or state level linear modeling to site-specific logistic modeling of local features. Comparisons between spatial datasets and field collected data are common, but local-scale data is preferred (Seiler 2005, Clevenger et al. 2015, Bartonicka et al. 2018). Animal occurrence or collision hotspot estimations have been used within these models to increase their predictive capacity (Finder et al. 1999, Ng et al. 2008, Vistintin et al. 2016). Models have also included information extracted from spatial datasets of landscape composition and other land cover or disturbance-related features (Chen and Wu 2014, Clevenger et al. 2015, Vance et al. 2017).

Once reliable models of WVC occurrence have been constructed, managers can form plans for mitigation of each impactful variable. Methods for modifying animal occurrence include changes to hunting regulations, removal of local attractants, and addition of local repellants to modify animal behavior or proactive urban planning that keeps development contained to areas where the animal involved does not frequently occur (Rea 2003, Hussain et al. 2007, Girardet et al. 2015). Road-crossing structures (i.e., under- and over-passes), when combined with fencing, and fencing alone have also been used to reliably keep animals off roadways (Rytwinski et al. 2017). Methods for modifying human behavior include reduction of traffic levels or speeds through transportation planning, increased enforcement of road safety regulations, or educational initiatives aimed at increasing driver awareness (Marcoux and Riley 2010, Gunson et al. 2011). Increasing motorist visibility and decreasing moose attraction has been achieved through roadside vegetation management (Rea 2003). It must be noted that the

effectiveness of roadside vegetation management is dependent upon the timing of treatment because removal of vegetation in the middle of the growing season can increase the nutritional value of future growth (Rea 2003). Increasing motorist visibility and awareness has also been achieved through increased lighting and signage, but motorists are easily habituated to signage that is year-round and stationary (McDonald 1991, Sullivan et al. 2004). Wildlife reflectors, devices used along roadways that are intended to either warn motorists of incoming wildlife or scatter light near roadways to scare away incoming wildlife, have been proven ineffective (Brieger et al. 2017).

Overall, undertaking the majority of these mitigation options will require cooperation between the Alaska Department of Fish and Game and the Alaska Department of Transportation and Public Facilities. In the following chapters, I provide insight into many of these issues in turn, with the goal of providing as much information to each department as possible, so that the issue of increasing MVCs in the Matanuska-Susitna Borough, and in Alaska at large, may be addressed. In Chapter 2, I discuss the variation in MVC rates through time throughout the urbanized areas of Alaska and the possible causes for the difference in MVC rates between boroughs. With Chapter 3, I address the site-specific characteristics of reported MVC sites and documented moose crossing sites within the Matanuska-Susitna Borough and address possible mitigation options for dealing with the increasing MVC rates in the area. Chapters 2 and 3 are in the style, tense, and person required for their submission into the scientific journals published by The Wildlife Society, and Chapter 2 is currently under review in one such journal. I conclude with Chapter 4, summarizing my findings and providing future research needs for mitigation of MVCs in Alaska.

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CHAPTER 2

TEMPORAL VARIATION IN MOOSE-VEHICLE COLLISIONS IN ALASKA[1]

ABSTRACT

Collisions between vehicles and wildlife have long been recognized to pose threats to motorists and wildlife populations. In addition to the risk of injury or mortality faced by the motorists involved in wildlife-vehicle collisions (WVC), other drivers are also put at risk due to road obstructions and traffic congestions associated with WVCs. Most WVCs in Alaska involve moose (*Alces alces*), an animal that is sufficiently large to pose a threat to property and human life when involved in collisions. We analyzed the temporal variation in the number of moose-vehicle collisions (MVCs) reported in the four most populous boroughs of Alaska between 2000 and 2012. We examined daily and annual trends in MVC rates and compared them to moose and human behavioral patterns to better understand possible mitigation strategies. Annual variation in MVC rates was linked to expected seasonal changes in the distribution of moose. MVC rates varied relative to expected moose activity patterns and traffic flow. The distribution of MVCs was skewed towards winter and towards hours of the day with less visibility. Fifty percent of the MVCs reported between 2000 and 2012 occurred where the commuter rush hours overlapped with dusk and dawn in winter. Knowledge of these temporal patterns can provide managers with practical mitigation options, such as the use of seasonal speed reduction, improved lighting strategies, dynamic signage, or partnerships with mobile mapping services.

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[1] Lucian R. McDonald, Terry A. Messmer, and Michael R. Guttery

INTRODUCTION

Human-wildlife conflicts are increasing in proportion to the growth in human population and per capita consumption of natural resources (Messmer 2000, Conover 2001). These conflicts include property losses, attacks on humans, crop and livestock losses, and any other negative interaction between wildlife and humans (Conover et al. 1995, Messmer 2000, Treves et al. 2006, Dickman 2010). Human-wildlife conflicts, in addition to resulting in the destruction of wildlife, impact the socio-economic livelihoods of people (Conover et al. 1995, Dickman 2010, Barua et al. 2013, Khumalo and Yung 2015). These conflicts can either be real or perceived, economic or aesthetic, social or political.

One consequence of human population growth and urbanization is increased wildlife-vehicle collisions (WVCs). Although WVCs have occurred since the introduction of motorized vehicles, the WVC rate has increased geometrically with increasing traffic volumes and speeds (Conover et al. 1995). Concomitantly, contemporary WVCs place motorists and wildlife at increased risk of mortalities and injuries. If WVCs are not sufficiently mitigated, we should expect the risks to motorists to increase as urbanization continues. These increased risks subsequently reduce the cultural carrying capacity of the wildlife population involved as seen with white-tailed deer (*Odocoileus virginianus*) and beavers (*Castor canadensis*) in the eastern U.S. (Kilpatrick and LaBonte 2003, Siemer et al. 2013).

Ungulates exhibit diverse life-history strategies as survival mechanisms across their range, including nomadic behavior observed in roe deer (*Capreolus capreolus*) across Europe, partial migration exhibited in red deer (*Cervus elaphus*) in Norway, and

migrations of pronghorn (*Antilocapra americana*) in Wyoming (Sawyer et al. 2005, Meisingset et al. 2017, Curiot et al. 2018). These survival strategies can affect their interaction with humans and contribute to seasonal variation in WVCs (Krauze-Gryz et al. 2017). Studies in Canada and the northeastern U.S. have documented seasonal variation in WVCs involving moose (*Alces alces*; Joyce and Mahoney 2001, Danks and Porter 2010). In Norway and Canada, the seasonal change in snow depth and temperature predicted fluctuations in moose-train collision (MTC) and moose-vehicle collision (MVC) patterns (Gunderson and Andreassen 1998, Dussault et al. 2006, Rolandsen et al. 2011). Krauze-Gryz et al. (2017) and Niemi et al. (2013) linked the life-cycle strategies of moose to the seasonal variation in MTCs in Poland and MVCs in Finland.

Anecdotal evidence suggests that MVC patterns reflect the seasonal constriction of the distribution of moose to areas where roads are more common, but little empirical evidence of such a trend exists to support this assumption. For example, in Alaska, more MVCs occur between November and February than in all other months combined (Del Frate and Spraker 1991). In south-central Alaska, moose typically cluster at lower elevations during the winter months as the snow depth in the mountains increases, thereby increasing moose population density in valleys (Ballard and Whitman 1988, Pritchard et al. 2013). Because valleys are also areas of urban sprawl, this seasonal variation in moose population density near roads should be reflected in the pattern of MVCs throughout the year (U.S. Census Bureau, 2010). In a 31-year study in Norway, Rolandsen et al. (2011) found the density of moose populations to be the most important factor explaining the variation in MVCs, and Dussault et al. (2006) and Seiler (2005) used moose population density to explain the variation in MVCs in Canada and Sweden.

Both traffic flow and moose activity peak daily in a bimodal crepuscular pattern, so the daily pattern of MVCs should reflect this difference, especially during the darkest months of the year (Steiner et al. 2014). Dussault et al. (2006) found that probability of MVCs in Canada increased 2-3 times higher at night. Gunderson and Andreassen (1998) in Norway and Joyce and Mahoney (2001) in Newfoundland reported MTC/MVC frequency to be highest between dusk and dawn.

Moose are the most common species involved in reported WVCs in Alaska (Alaska Department of Transportation and Public Facilities [ADOTPF], unpublished data). Between 2000 and 2012, ADOTPF documented 9,949 MVC in the state (ADOTPF, unpublished data). These MVCs resulted in 23 human fatalities, 118 incapacitating injuries, and approximately 1,400 minor injuries (ADOTPF, unpublished data). The ADOTPF estimated that $33,000 is lost every time an MVC occurs in the state, based on the medical and vehicle repair costs alone.

The objective of our research was to delineate temporal trends in MVCs across Alaska to assist managers in developing potential MVC mitigation strategies. We expected the rate of MVCs per hour and per day to be distributed uniformly among years and across the four study areas due to the similar daily movement behavior of moose and people. We also expected the rate of MVCs per hour and per day to be unequally distributed across seasons due to changes in ambient lighting conditions between summer and winter. Due to the crepuscular nature of moose, we expected peaks in MVC rates per hour during dusk and dawn as opposed to other periods of the day. Because traffic patterns tend to change between the week and weekend, we expected the distribution of MVCs per day and per hour to be unequal between business days and weekend/holidays.

We also expected the number of hours with sunlight per day and the day of the year to be adequate predictors of MVC rates across study areas. Assuming our hypotheses about the hourly and daily distribution of MVCs were valid, we expected temporal clustering at the intersection of the daily and annual peaks in MVCs across study areas.

STUDY AREA

We conducted our study within four Alaskan boroughs: the Municipality of Anchorage (ANC), the Fairbanks-North Star Borough (FNB), the Kenai Peninsula Borough (KPB), and the Matanuska-Susitna Borough (MSB). The ANC, KPB, and MSB are situated within south-central Alaska within 58.6-63.5°N latitude and 146.4-154.7°W longitude. Topography within the ANC, KPB, and MSB ranges from sea level to a respective peak of 2,441, 3,480, and 4,443 meters above sea level. The FNB is situated within interior Alaska between 64.2-65.5°N latitude and 143.8-148.7°W longitude and encompasses a range of elevations between 83 and 1788 meters above sea level.

Between 2000 and 2012, the mean annual temperature was 3°C in south-central Alaska where the temperature oscillated from -26°C in winter to 24°C in summer (National Oceanic and Atmospheric Administration [NOAA] 2012). Mean annual precipitation ranged between 32 and 55 cm between 2000 and 2012, while mean annual snowfall ranged between 93 and 342 cm. The mean annual temperature was -2°C in interior Alaska where the temperature ranged from -42°C in winter to 24°C in summer (NOAA 2012). Mean annual precipitation ranged between 21-35 cm between 2000 and 2012, while mean annual snowfall ranged between 63-197 cm.

These boroughs were chosen because they represent the majority of the human

population (82%) and the majority of the MVCs (88%) reported in Alaska during the study period between 2000 and 2012. As of the 2010 census, the most populous area of the state was the ANC, which accounted for 41% of the 700,000 residents of Alaska and encompassed an area of 5,083 km^2. The FNB, KPB, and MSB had similar human population sizes, accounting for 14%, 13%, and 13% of the populace respectively. The respective areas of the FNB, KPB, and MSB are 19,280, 64,107, and 65,418 km^2, and the human populations were highly concentrated into a small portion of their respective borough (Fig. 2-1).

The ANC is located within Game Management Unit (GMU) 14C, which had an average estimated moose density of 0.35±0.00 moose/km^2 according to the Alaska Department of Fish and Game (ADFG) moose management reports that represent the years between 1999 and 2013 (ADFG 2002-2014). The average estimated moose density of GMU 20B, which surrounds FNB, was 0.53±0.07 moose/km^2 (ADFG 2002-2014). In KPB, the majority of the road system and human population is located in the western portion of the borough which is within GMU 15 and had an estimated moose density of 0.34±0.08 moose/km^2 during this time (ADFG 2002-2014). In MSB, most of the human population resided within GMU 14A and GMU 14B, which had an estimated moose density of 0.62±0.08 moose/km^2 (ADFG 2002-2014).

Within ANC (34.4%), FNB (28.5%), KPB (37.9%), and MSB (45.7%), a large share of the reported MVCs occurred on a state highway in each the four boroughs and only three of the state highways bisected these boroughs. Six local roads accounted for more than 5% of the MVCs in a given borough (Fig. 2-1). Because the boroughs accounted for large areas of the state, ambient light conditions could differ among

boroughs depending upon the time of year. The KPB is at much lower latitude than the FNB, so the hours of sunlight per day differ by as much as two hours in the winter.

METHODS

Each time an MVC was reported by a driver within the state of Alaska, a law enforcement officer filed a report on the incident which included information on the date, time, and approximate location of the collision as well as descriptive variables such as the number and type of injuries, number of animals, and number of vehicles involved. To facilitate this research, we accessed the statewide database of MVC reports compiled by ADOTPF from 2000 to 2012. We were also provided access to daily traffic counter data for the state highways in each borough. Because the state highways represent major transportation corridors within each borough, we used these data as an index of daily traffic fluctuation. These data included a count for each lane of each state highway at a central point within the borough from January 1st to December 30th of each year. We summarized traffic counts across all lanes and averaged traffic count data from areas bisected by two state highways to produce a single traffic index value for each day of each year for each borough.

We filtered the MVC report data using R software (R Core Team 2018), with the package Tidyverse (Wickham 2017), to only include the ANC, FNB, KPB, and MSB observations without missing accident date/time information and removed variables that were not relevant to the analysis. The resulting data table consisted of 8,794 observations described by accident date/time and borough. Using the accident date/time variable, we created variables classifying each observation by the hour of the day, day of the week,

ordinal day of the year, year, and a seasonal factor representing a period of the annual life-cycle outlined for moose by Ballard and Whitman (1988). We also used the accident date/time and the centroid of each borough to classify each observation with the approximate sunrise, sunset, and sun altitude using R software with the package 'Suncalc' (Agafonkin and Thieurmel 2018). Using these sunrise and sunset times for each observation, we calculated the number of hours per day with sunlight to capture the change in the photoperiod throughout the year. We classified each observation by whether the accident date corresponded to a recognized U.S. holiday using R software, with the package Tis (Hallman 2017). Finally, we merged the ADOTPF traffic counter data with the MVC data based on the accident date.

Because moose activity was expected to increase during dusk and dawn, we used the sun altitude variable to categorize each observation as night, dawn, day, or dusk. Based on the astronomical definition of twilight, we defined night as an altitude below -18 degrees and day as an altitude above zero degrees. We defined dusk and dawn as an altitude between -18 and zero degrees and separated dawn and dusk based on the hour of the day. To evaluate whether the mean frequency of MVCs per hour was greater during dawn and dusk than day and night and whether the seasonal difference in lighting affects these differences, we performed Welch 2-sample t-tests on eight subsets of the data. We filtered the observations to only include dusk or dawn, night or day, and winter or summer observations and compared the mean frequency of MVCs per hour between the two pairs of time groupings (e.g. winter, dusk > day or summer, dusk > day).

Using the initial 8,794 observations, we constructed additional frequency tables by summarizing the count of MVCs per day based on the year, borough, season,

weekend/holiday, and hours of sunlight per day variables. We performed a Pearson's χ^2 test with a simulated p-value based on a Monte Carlo test with 2,000 replicates to determine whether the distribution of MVCs per day was equal among these groups (Agresti 2007, Danks and Porter 2010). We used the number of hours of sunlight per day as an explanatory variable to predict the frequency of MVCs in a Poisson-distributed generalized linear model using R software, with the package Mgcv (Wood 2004). We introduced the daily traffic count and borough as random effects to improve the model. Then, we constructed a generalized additive mixed model with day of the year as the explanatory variable predicting the frequency of MVCs per day. The model was constructed using cyclic penalized regression splines with matching ends, 10 degrees of freedom, and a log-linked Poisson error distribution (Krauze-Gryz et al. 2017). As an offset, we calculated the natural logarithm of the traffic index associated with each observation. To increase the predictive capacity, we added a random effect indicating whether the day was a weekend/holiday or a business day.

Finally, we used the accident date/time variable from the original 8,794 observations to create a time of the day variable by adding the hour of the day to the minute of that hour divided by 60 min. This time of the day variable was then used as the y-axis of a kernel density surface where the x-axis indicated the day of the year for each observation following the same procedure typically used to compute a kernel density surface of spatial data using R software, with the package Ks (Krauze-Gryz et al. 2017, Duong 2018). We computed contours representing the smallest area that represented 50% of the data to evaluate temporal clustering of reported MVCs in each borough. By plotting these contours, we were able to visualize the intersection between peaks in

MVCs per day and peaks in MVCs per hour throughout the year and compare them to the life-cycle periods of moose in Alaska (Ballard and Whitman 1988).

RESULTS

The KPB (27%) and MSB (27%) accounted for most of the reported MVCs in the state, followed by the ANC (21%) and FNB (14%). Between 2000 and 2012, MVC rates across the state were stable (Fig. 2-2). The distribution of MVCs throughout the day skewed away from noon and half of all MVCs in the state occurred between the hours of 1700 and midnight (Fig. 2-3). Based on the Pearson's χ^2 tests, the distribution of collisions per hour did not differ by year (χ^2 = 745, P = 0.797), borough (χ^2 = 227, P = 0.226), or weekend/holiday group (χ^2 = 48, P = 0.121). The distribution of collisions per hour among seasons differed (χ^2 = 335, P = 0.023) with winter contributing to the highest proportion of MVCs per hour.

During winter, the mean frequency of MVCs per hour was greater at dusk than at day (t = 8.020, df = 104.1, P = <0.001) and at night (t = 2.097, df = 121.9, P = 0.019) and greater at dawn than at day (t = 6.677, df = 89.6, P < 0.001), but the mean frequency of MVCs per hour was less at dawn than at night (t = -2.480, df = 129.63, P = 0.007). During summer, the mean frequency of MVCs per hour was greater at dusk than at day (t = 8.245, df = 41.9, P = <0.001) and at night (t = 10.080, df = 41.7, P = <0.001), and greater at dawn than at day (t = 7.388, df = 117.8, P = <0.001) and at night (t = 11.363, df =112.2, P = <0.001).

The distribution of MVCs per day was skewed towards the winter months. Based on the Pearson's χ^2 tests, the distribution of collisions per day differed among years (χ^2

= 171, P < 0.001), boroughs (χ^2 = 140, P < 0.001), seasons (χ^2 = 409, P < 0.001), and weekend/holiday group (χ^2 = 514, P < 0.001). According to our generalized linear model, the number of hours of sunlight per day had a negative effect on the number of MVCs per day (z = -42.1, P < 0.001), but the predictive capacity of the model was low (R^2 = 28.7%). The model improved when the traffic index was added as an interactive factor (R^2 = 35.6%), but the best model included an interaction between hours of sunlight per day and borough (R^2 = 52.8%, Fig. 2-4).

When we isolated annual MVC cycles for each borough, the number of collisions per day increased at the beginning of winter in the KPB and the MSB to between 1.5 and 2.0 MVCs per day while staying consistently between 1.0 and 1.5 MVCs per day in ANC and FNB (Fig. 2-5). We observed a consistent drop in MVCs per day near the end of winter in all boroughs. The deviance explained by our generalized additive mixed model, which accounts for a smoothed day of the year term (χ^2 = 1018, P < 0.001), a random effect based on the borough, and an offset of daily traffic count, was 84.3%. When we added a factor indicating the year, season, or whether the MVC occurred on a business day or a weekend/holiday, there was no change in the predictive capacity of the model.

Using kernel density estimation, we were able to visualize the intersection between daily and annual peaks in MVC frequency using a point pattern of time of the day plotted against day of the year for each observation. Fifty percent of all MVC observations were isolated to 20.3% of the temporal plane within the ANC, 17.8% of the temporal plane in the FNB, 13.3% of the temporal plane in the KPB, and 13.6% of the temporal plane in the MSB. These concentrations are represented by contours in Fig 2-6 which demonstrated that MVC observations were densely clustered near dawn and dusk

during fall and winter.

DISCUSSION

The temporal distribution of MVCs in our study areas reflected daily and seasonal fluctuations in expected moose behavior and traffic flow. As moose migrated to lower elevations in winter, they became more likely to encounter traffic. The concentration of wintering moose corresponded with decreased visibility due to increasingly dark days, especially during the commuter rush hours near dusk and dawn. Krauze-Gryz et al. (2017) reported similar seasonal peaks in wildlife-train collisions near dusk and dawn, which is a commonly reported phenomenon among animal-vehicle collision studies (Haikonen and Summala 2001, Smith and Dodd 2003, Danks and Porter 2010, Chen and Wu 2014, Bartonicka et al. 2018).

As expected, the rate of MVCs per hour was distributed equally across years. The pattern of MVCs throughout the day corresponds to the expected crepuscular pattern of moose activity and traffic flow, which peaks during the morning and evening commuter rush hours (Akerstedt et al. 2001, Steiner et al. 2014). The rate of MVCs per day was not distributed equally across years. If we assume the moose density near roads is due to snow depth in the mountains, then a changing distribution of MVCs per day among years could be better explained by weather patterns, which are less predictable (Ballard and Whitman 1988, Steiner et al. 2014). However, weather stations in Alaska are few in number and do not represent all of the boroughs where MVCs are common. Future study of MVCs in relation to snow or temperature would require the addition of weather stations either near the most impacted roads or near high elevation areas from which

moose in the area would be moving.

As hypothesized, the rates of MVCs per hour and per day were not equally distributed across seasons, and there was a higher rate of MVCs per hour at dusk and dawn compared to the hours of the day. During the winter solstice in these four areas of Alaska, sunrise is between 1000 and 1100 and sunset is between 1500 and 1600 depending upon the latitude, yet sunlight is available past midnight during the summer solstice. These changing light conditions throughout the year cause dusk and dawn to overlap the morning and evening commuter rush hours during winter, but keep the commuter rush hours during summer completely lit by ambient light. Concurrently, these populations of moose are expected to constrict their range to lower elevations, increasing the likelihood that motorists come into contact with moose during the winter (Ballard and Whitman 1988, McDonald 1991). During winter, the rate of MVCs per hour was greater at dusk than at night, but the rate of MVCs per hour was less at dawn than at the night. In a study focused on the general timing of traffic accidents, Akerstedt et al. (2001) reported that late afternoon/nighttime accidents have a more pronounced peak than early morning accidents due to a variety of factors including visibility, intoxication, impatience which leads to speeding, and drowsiness. As nighttime in winter is especially hazardous due to weather and light conditions, the increase in moose activity at dawn may be overshadowed by the lack of visibility at night. The greater rate of MVCs per hour at dawn as opposed to at night in the summer may be more attributed to increased moose activity at dawn than visibility.

The distribution of MVCs per day was not equally distributed among the two groups, business day and weekend/holiday, but the addition of this factor did not increase

the predictive capacity of our generalized linear model. The difference in traffic patterns between business days and weekend/holidays is likely sufficiently explained by the traffic index we used to offset our model. Using the day of the year as a predictor in our generalized additive mixed model was the best option for delineating temporal trends in MVCs because the cyclic day of the year variable roughly parallels the fluctuation in hours without sunlight per day and seasonal moose population density (Steiner et al. 2014). Krauze-Gryz et al. (2017) also found the day of the year to be a useful variable to represent the seasonal change in animal-train accidents. As seen from the kernel density contours (Fig. 2-6), half of all reported MVCs in each borough occurred during the winter either just before sunrise or just after sunset.

This temporal clustering as well as the negative relationship detected by our generalized linear model of MVC rate as a function of hours of sunlight per day may be attributed to artificial lighting. Based on the December 2012 Visible Infrared Imaging Radiometer Suite Day/Night Band image of artificial lighting presence, mean reflectance across the roads of the ANC and FNB was near 62.4% and 15.5% respectively, while the mean reflectance across roads in the KPB and MSB were both near 4.4% (Elvidge et al. 2017). The ANC, while being the most populous area, had the lowest MVC rate as a function of traffic among the four boroughs in this study. The FNB was equal in population to the KPB and MSB yet had far fewer MVCs as a function of traffic. Conflicting results have been reported regarding the effects of artificial lighting on mitigating WVCs. Reed and Woodard (1981) found no evidence to support using artificial lighting to reduce deer-vehicle collisions in Colorado, but McDonald (1991) found that artificial lighting led to a 65% decrease in MVCs on Alaska Highway 1. As a

way to reduce overall light pollution and save costs, lighting structures can be strategically placed within areas of concentrated MVC risk and lit only during the winter rush hour when traffic levels and moose activity peak (Rolandsen et al. 2011, Gaston et al. 2014).

Permanent "safety corridors", designated lengths of the road system with reduced speed limits and higher safety fines, have reduced serious motor-vehicle accidents within highly trafficked areas by 46% since their introduction to Alaska in 2006 (Kramer et al. 2017). The use of seasonal dynamic signage and seasonally reduced speed limits could provide a similar mitigation option for MVC hotspots throughout the state. Mastro et al. (2010) reported that motorists could not see deer decoys standing at the edge of the road until they were within 50 m of them. When driving over 75 km/h, this would be an inadequate braking time. The Alaska state highway system, on which 38% of the reported MVCs occurred, has speed limits that range from approximately 80-105 km/h. Speeding fatalities accounted for 35-46% of all motor-vehicle fatalities between 2005 and 2011, and 66% of surveyed drivers admitted to occasionally driving faster than 113 km/h in a 106 km/h speed zone (Kramer et al. 2012). A reduction of the speed limit to lower than 75 km/h during periods of high MVC threat could increase driver visibility and reduce braking time.

Sullivan et al. (2004) reported a 51% reduction in deer mortality when drivers, influenced by a seasonal signage treatment, followed the speed limit. Within the KPB and the MSB, dynamic signage, which is updated each month to show the number of MVCs that have occurred since July 1st, has been implemented since the 1990's as a part of a public awareness program to reduce MVCs (Del Frate and Spraker 1991). The use of

strategically placed warning signs can keep drivers alert to the threat of MVCs, but drivers easily habituate to stationary signage. New signage should include dynamic messaging or should be removed seasonally based on MVC threat (Sullivan et al. 2004, Hardy et al. 2006).

As we have entered the information age, modernized alert systems could be implemented in mobile mapping services, such as Google or Apple maps, with the partnership of local government agencies. If these government agencies were to provide the mapping service with spatial and temporal MVC hotspots, an alert could be sent to drivers using the map application before they enter an area of high MVC probability, similar to the way map services warn drivers about upcoming traffic congestion. Further study is required to isolate the spatial extent of MVC hotspots within the state, but this mitigation option could be a promising alternative as more people adopt smartphones.

Our research provides new insight into temporal patterns in MVC rates in Alaska that can be used to inform mitigation efforts. However, it is likely that many other factors influence MVC rates through both space and time. For example, differences in latitude and elevation gradients may lead to different behavioral adaptations than those documented by Ballard and Whitman (1988) for moose in south-central Alaska, especially in the moose population near FNB. In future studies, weather patterns, especially snow depth patterns, should be explored as an index of moose population density. In conjunction with artificial lighting, factors such as road geography, vegetation height, vegetation type, and weather may influence the driver’s visibility as well as the moose’s affinity for crossing at the site. Further study of Alaskan MVCs should focus on site-specific factors that lead to spatial and temporal hotspots.

MANAGEMENT IMPLICATIONS

We were able to delineate the temporal distribution of MVCs within the state of Alaska and explain the daily and seasonal fluctuations using expected moose behavioral trends and traffic flow. This analysis could be replicated for any management unit that needs a preliminary assessment of possible WVC mitigation. Within the state of Alaska, the winter peaks in MVCs could be mitigated with dynamic or seasonal signage, seasonally decreasing speed limits, or with improved lighting strategies during the winter rush hour. Partnerships with mobile mapping services could become a promising alternative to seasonal mitigation practices.

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FIGURES

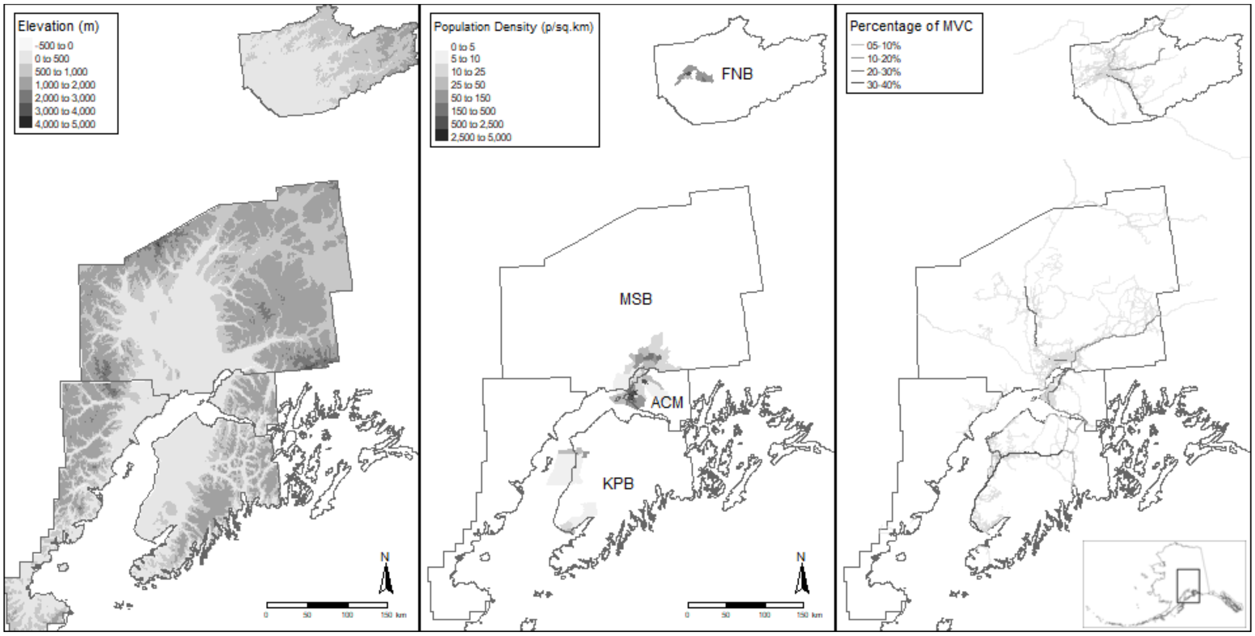

Fig 2-1. Map of study areas including elevation, population density, and percent of moose vehicle-collisions (*Alces alces*; MVC) on the road system within four Alaskan boroughs: the Municipality of Anchorage (ANC), the Fairbanks-North Star Borough (FNB), the Kenai Peninsula Borough (KPB), and the Matanuska-Susitna Borough (MSB), Alaska, USA, 2000-2012.

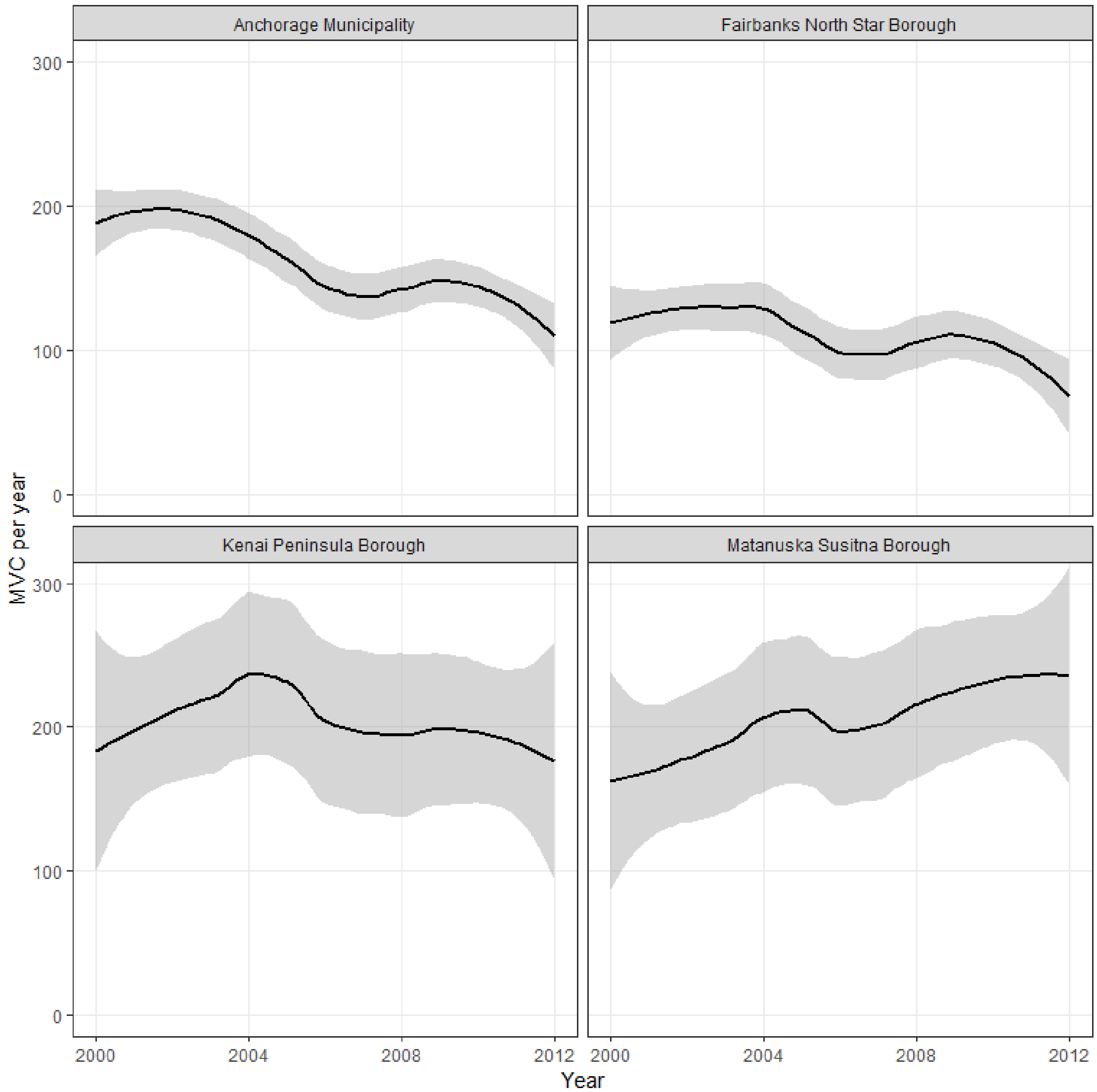

Fig 2-2. Moose-vehicle collision (*Alces alces*; MVC) trends between 2000 and 2012 in the four most populated areas of Alaska, USA.

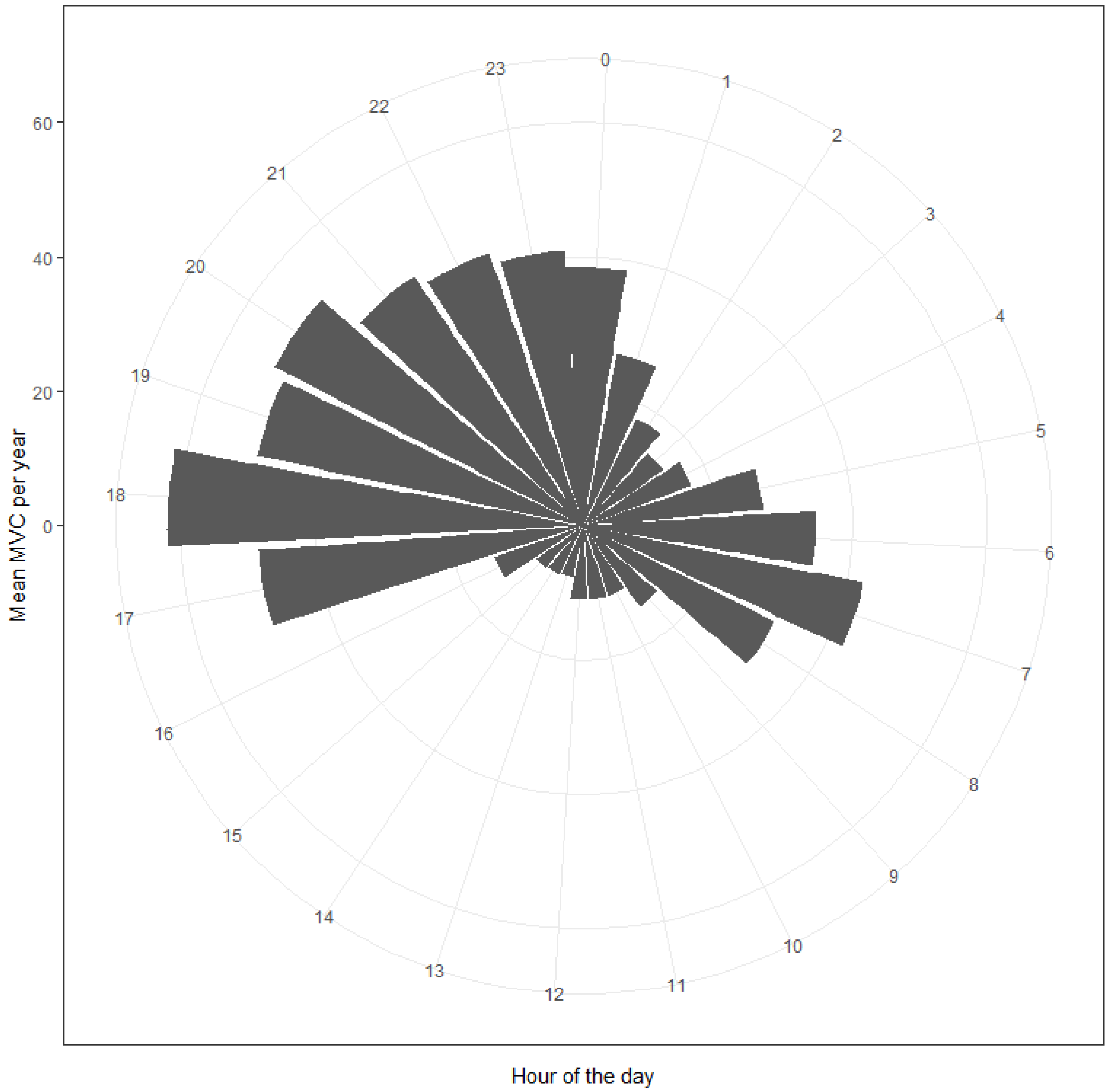

Fig 2-3. The distribution of moose-vehicle collisions (*Alces alces*; MVC) reported between 2000 and 2012 in four boroughs of Alaska, USA. The MVC frequency is categorized by the hour of the day from 12 AM (0) to 11 PM (23) and the year, and the average count of MVC per hour is presented.

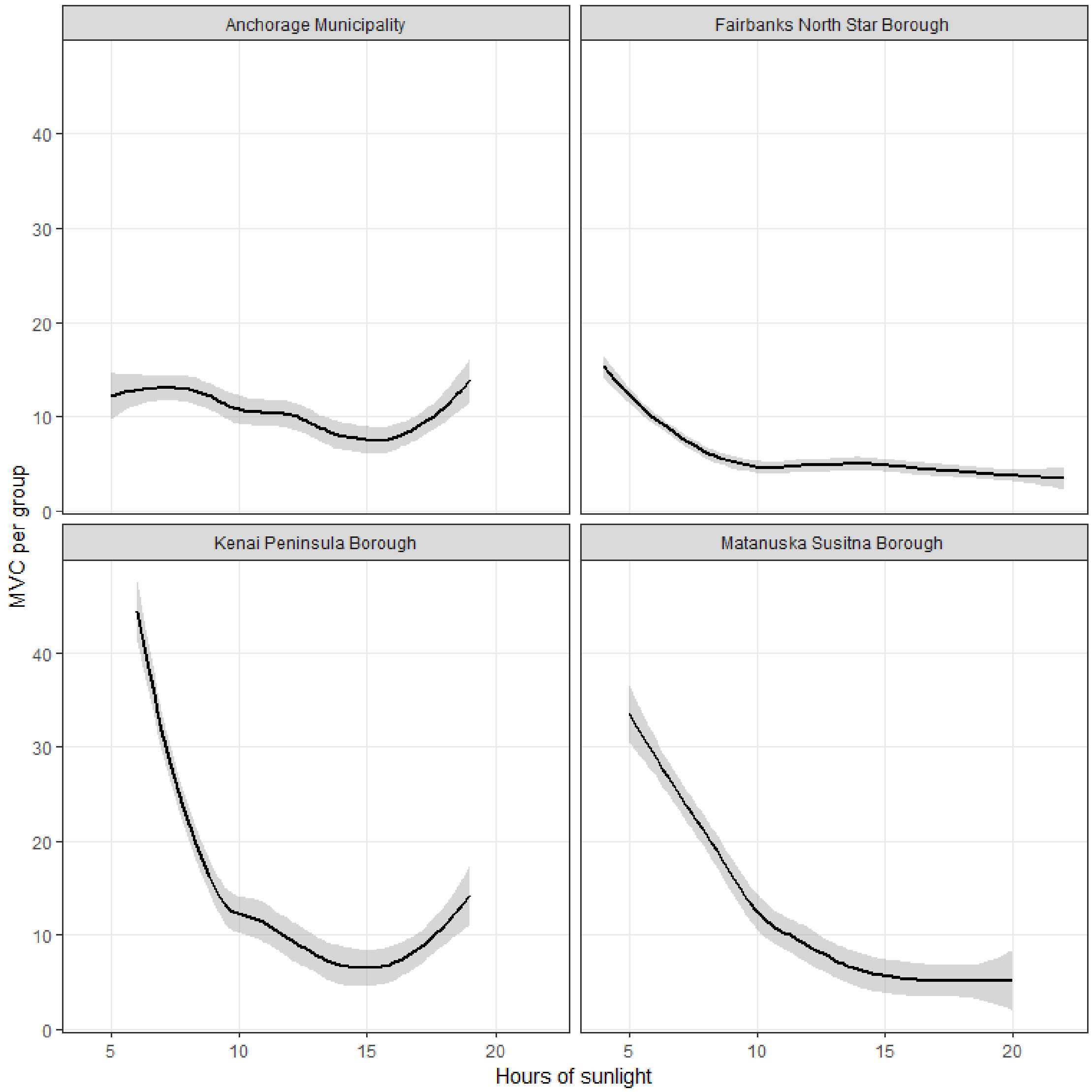

Fig 2-4. Moose-vehicle collision (*Alces alces*; MVC) frequency modeled as a function of hours of sunlight per day, Alaska, USA, 2000-2012.

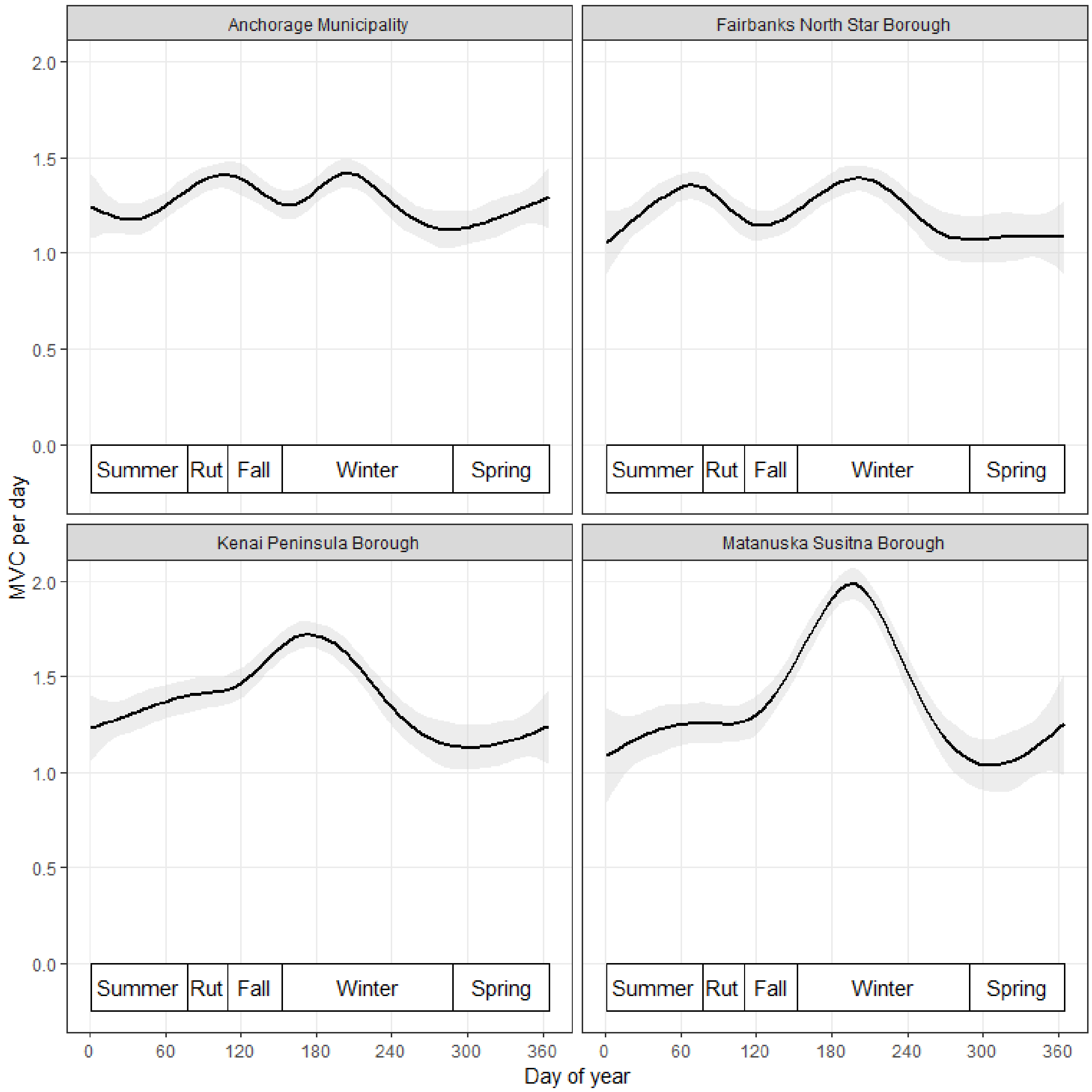

Fig 2-5. Moose-vehicle collisions (*Alces alces*; MVC) per day modeled as a function of the ordinal day of the year with a random effect indicating the borough and an offset based on traffic fluctuation, Alaska, USA, 2000-2012. The y-axis is scaled to start the year at July 1st to emphasize the winter peak in MVC rates.

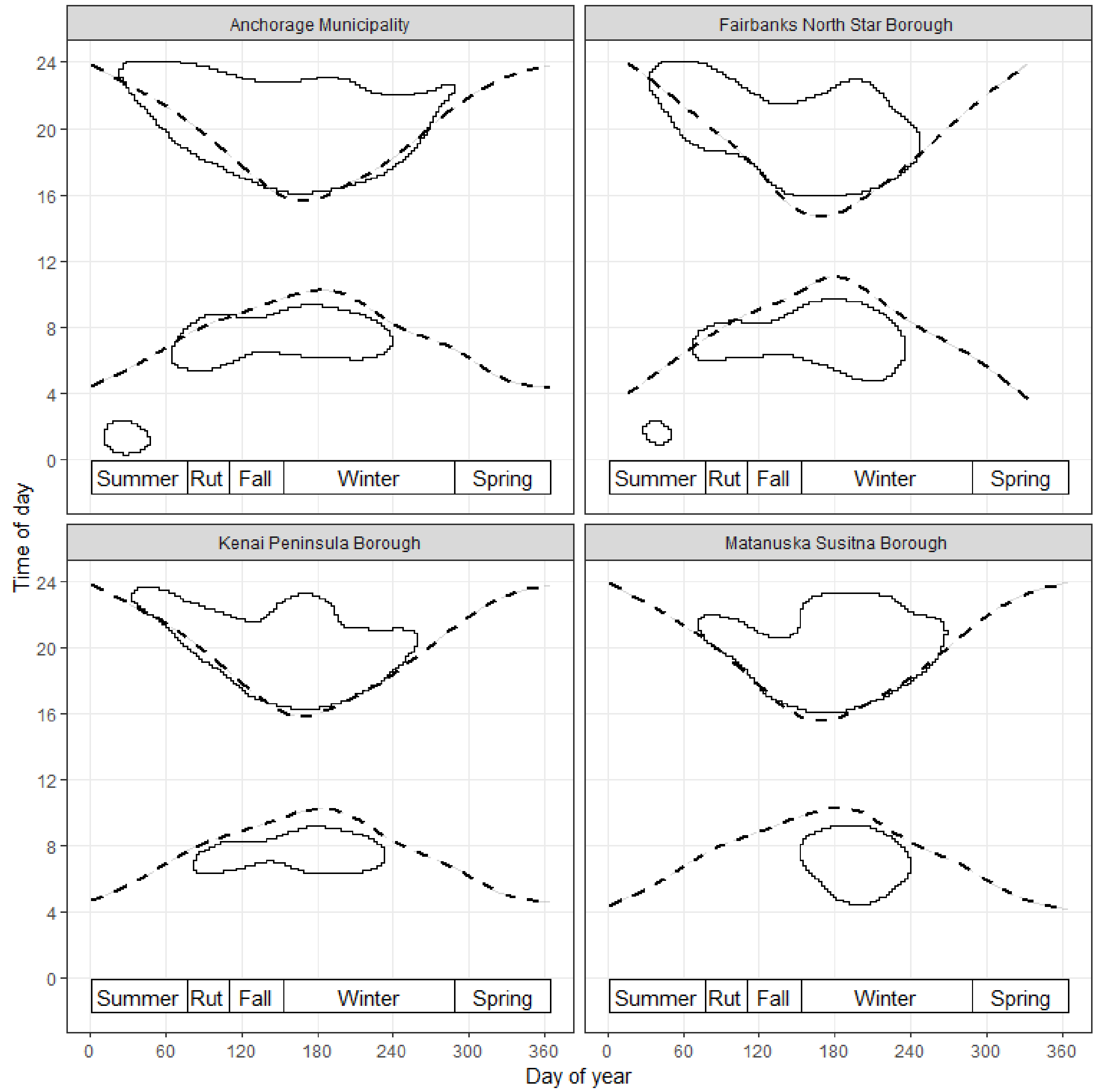

Fig 2-6. Temporal kernel density surface represented by a contour outlining the smallest possible area that contains 50% of the moose-vehicle collision (*Alces alces*; MVC) observations in each borough, Alaska, USA, 2000-2012. Sunrise and sunset times are demarcated with dashed lines to represent the changing day length and the timing of dusk and dawn.

CHAPTER 3

MOOSE-VEHICLE COLLISION RISK FACTORS IN THE MATANUSKA-SUSITNA BOROUGH OF ALASKA[2]

ABSTRACT

Human-wildlife conflicts are increasing as human populations continue to grow and encroach into wildlife habitats. Increasing trends in the number of reported wildlife-vehicle collisions (WVCs) provide tangible evidence of anthropogenic impacts on wildlife as well as increasing threats to human health and safety. Of particular concern are increasing WVCs involving large-bodied ungulates such as moose (*Alces* spp.) because of the increased risk of property damage, personal injuries, and human fatalities. Managers planning to mitigate the impacts of these moose-vehicle collisions (MVCs) will require region specific data to understand where and when these incidents occur. To address this information need, we collected and analyzed local and regional scale land cover and road geometry data from August 2016-November 2018 at reported MVC sites in south-central Alaska, USA with a rapidly growing human population. We compared these data to similar data collected at random locations near documented MVC sites and at locations where moose that were fitted with global-positioning system (GPS) transmitters crossed highways. We used generalized additive mixed models (GAMMs) to delineate which of the variables impacted the risk of both moose road crossings and MVCs. Moose road crossings were influenced by approximations of spatial, seasonal, and daily moose density as well as the proportion of deciduous-coniferous and coniferous

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[2] Lucian R. McDonald, Terry A. Messmer, and Michael R. Guttery

forest in the area and the number of possible corridor or land cover types surrounding the site. The best MVC risk model was described by expected seasonal and daily changes in moose density and local scale measurements, including the sinuosity of the road, the height of vegetation near the road, and the angle between the road surface and the roadside. Future transportation planning should focus on roadside vegetation removal, implementation of lighting structures where MVC risk is high, and the construction of roads with less sharp curves and less steep downward angles that can funnel wildlife onto the roadway. Urban planning should focus development inward to keep motorists centralized to areas of high development, which our radio-marked moose tended to avoid.

INTRODUCTION

Human-wildlife conflicts are increasing as human populations continue to grow and encroach into wildlife habitats (Messmer 2000). These conflicts include increased risks to human health and safety, wildlife mortalities, property loss and damage, regulatory constraints, and more species being at risk of extirpation and extinction (Messmer 2000). The increasing number of wildlife-vehicle collisions (WVCs) reported provides tangible evidence of anthropogenic impacts on wildlife and increased risk to human health and safety (Sullivan and Messmer 2003, Langley et al. 2006, Bissonette et al. 2008, Huijser et al. 2008).

The risk of WVCs to motorists and wildlife are increasing globally (Saenz-de-Santa-Maria and Telleria 2015, Mohammadi and Kaboli 2016, Bartonicka et al. 2018). In urban areas, increased traffic volumes and speeds have been linked to increased risk of WVC (Grilo et al. 2009, Morelle et al. 2013, Brieger et al. 2017). Along the urban-

wildlife interface, new development and the increased access to these areas constitutes a new hazard to animals that previously experienced limited exposure to vehicular traffic. The consequence of this development and access is exacerbated fragmentation of habitats and loss of connectivity between habitat patches (Messmer 2000, Davenport and Davenport 2006, Coffin 2007).

The locations of WVCs are typically clustered in both space and time and depend on a variety of interacting factors that vary in scale and depend upon the species of interest and location of study (Gunson et al. 2011, Clevenger et al. 2015, Crawford and Andrews 2016). The risk of a WVC depends on three interacting factors: 1) that an animal will cross a road at a particular location and time, 2) that a motorist will bisect the crossing location at the same time, and 3) that the motorist can see and react to the animal in time to avoid a WVC (Forman et al. 2003, Seiler 2005, Chen and Wu 2014). Extensive research has shown that combinations of these three factors can be used to model WVC risk (Forman et al. 2003, Coffin 2007, Gunson et al. 2011, Steiner et al. 2014).

The predictive ability of WVC models can be further enhanced by incorporating factors which may influence the probability of animal presence on a roadway. These factors include spatial and temporal density of animals, proximity to attractants such as forage, preferred land cover, or travel corridors, and proximity to repellants such as fencing or urban development (Rea 2003, Cserkesz et al. 2013, Steiner et al. 2014, Bartonicka et al. 2018). Average Annual Daily Traffic (AADT) flow and road classifications have been the main indices used to model motorist presence, though the reliability of these parameters has been questioned (Bissonette and Kassar 2008, Bartonicka et al. 2018). The probability that a motorist will stop in time to avoid a WVC

can be affected by visibility and the degree of impairment or distraction of the motorist. Motorist visibility is impacted by the speed of the vehicle, weather or light conditions, perceived safety of the motorist, the presence of obstructions along the roadside (i.e. verge), and roadway characteristics, such as road width, angle between the road and the verge, and road sinuosity (Seiler 2005, Dussault et al. 2006, Antonson et al. 2015, Clevenger et al. 2015).

Vehicular collisions involving large ungulates are of particular concern due to the increased risk of human injury or fatality. In northern boreal regions, where large-bodied ungulates such as moose (*Alces* spp.) are more common, moose-vehicle collisions (MVCs) are likely to cause property damage, serious injuries, or human fatalities than other types of WVCs (Niemi et al. 2017). Most WVCs in Alaska involve moose, and the Alaska Department of Transportation and Public Facilities (ADOTPF) has estimated an average overall cost of $33,000 for each MVC that occurs within the state (S. E. Thomas, ADOTPF, personal communication). The Matanuska-Susitna Borough of Alaska is the fastest developing area of the state and has a high density of moose (*A. alces alces*; U.S. Census Bureau 2010). Within Game Management Unit 14A, which encompasses the core area of the borough populated by humans, moose density is approximately 1.6 moose per km^2 (T. C. Peltier, Alaska Department of Fish and Game [ADFG], personal communication). As such, most residents may be somewhat aware of the hazards and consequences of being involved in a MVC, yet the number of MVCs reported in the borough continues to increase. Since 2015, the area has averaged approximately 315 MVCs per year, as opposed to the average of 250 reported MVCs per year between 2000 and 2012 (McDonald et al., In Review). Reporting rates can be as low as 50% depending

upon the damage to the vehicle, but studies relying on partial reporting can still successfully predict WVC risk (Snow et al. 2015).

We incorporated data collected at MVC sites, as well as commonly available spatial data, into two generalized additive mixed models (GAMMs) to identify factors contributing to both moose presence on the road network and MVC risk. Our objective was to determine the effect of manipulating the contributing factors within each model to develop possible mitigation strategies for decreasing MVC risk.

STUDY AREA

We conducted our study within the Matanuska-Susitna Borough in south-central Alaska. The area has a human population of approximately 100,000, and has averaged 3.4% growth per year since 1990, as opposed to the state average of 1.2% growth per year (U.S. Census Bureau 2010, E. Sandberg, Alaska Department of Labor and Workforce Development, personal communication). Our study focused on the south-central area of this borough, between 149.7-151.1°N longitude and 61.2-62.5°W latitude, where the majority of the human population resides (Fig. 3-1; U.S. Census Bureau 2010). The topography of the area ranges between sea level and a peak of 4,443 m above sea level.

Throughout the year, ambient light conditions change dramatically from nearly 24 hours of sunlight during the summer solstice to nearly 24 hours without sunlight during the winter solstice (Agafonkin and Thieurmel 2018). The average annual temperature is 8.1℃ with the average minimum temperature falling to -12.6 ℃ in winter and the average maximum temperature rising to 20.9 ℃ in summer. In summer, average

precipitation varies between 4 and 7 cm per month. In winter, average snowfall varies monthly between 20 and 30 cm (Western Regional Climate Center 2016). Forest vegetation typically consists of alders (*Alnus* spp.), cottonwoods (*Populus* spp.), willows (*Salix* spp.), birches (*Betula* spp.), or spruces (*Picea* spp.). The moose population in this area is primarily managed under ADFG Game Management Unit (GMU) 14A, which had an approximate population of 8,756 (±1,171) moose in 2018 (T. C. Peltier, ADFG, personal communication).

As classified by ADOTPF, the road network within our study area consisted of approximately 270 km of highway (28.1 m/km^2), 337 km of major (35.0 m/km^2), 262 km of medium (27.2 m/km^2), and 3,073 km of minor or lower roads (319.5 m/km^2; ADOTPF 2016). Each classification corresponds to the expected utilization of the road, where traffic volume is typically higher on highways and gets lower from major to minor roads. Daily traffic counts at the southern extent of our study area in 2016 increased from approximately 13,000 vehicles per day in late February, near the middle of winter, to approximately 52,000 vehicles per day in early September, the end of tourist season and near the middle of the early moose hunting season. The average annual daily traffic count for the highway, major, and medium roads in our study area was 3,515 vehicles per day (ADOTPF 2017*a*).

METHODS

We began collecting data for this study in August 2016. We received notifications of reported MVCs from the Alaska Moose Federation (AMF) and the local law enforcement dispatch office. Prior to March 2017, AMF provided us with the reported

date and time of each MVC along with the geographic coordinates of the collision site. Beginning in March 2017, the local law enforcement dispatch office directly provided the reported date, time, and location of each MVC using an automated messaging system. Once we received a MVC report, we visited the reported location and recorded a GPS waypoint using the GPS Receiver HD iPhone app (Petosoft, London, UK) and a GLO for Aviation Bluetooth-connected GPS Receiver (GARMIN International, Olathe, KS, USA) and named each MVC in numeric order. Using R software, we selected two random non-collision locations along the road system within 10 km but farther than 2.5 km of the MVC waypoint (Mountrakis and Gunson 2009, R Core Team 2018). All random sites were labelled in a numeric order parallel to the associated MVC site to easily manage the database (e.g. MVC site 1 would be associated with control site 10001 and 20001).

At each MVC and reference site, we documented: current date/time, reported date/time of MVC, speed limit, number of roadway lanes, width of lanes, width of shoulders, presence of a median, presence of moose warning signage within sight, presence and depth of snow, presence of road construction, evidence of MVC (e.g. moose tracks, blood spatter, car parts, or tire marks), presence of fencing, type of observed fencing, position of fencing in relation to collision, presence of bodies of water, and the presence of adjacent residential or commercial property. Within the verge, the area on each side of the roadway that is between the road and the adjacent forest, we recorded the depth of the ground in relation to the road surface and the height and type of vegetation (Fig. 3-2; Viereck et al. 1992). Within the context of motorist visibility, we considered the forest edge to be vegetation above 2.5 m, as it is unlikely a moose would be taller than this height. We recorded the verge data at 2 m increments from the road to the

maximum motorist scanning distance (20 m from the road; Mastro et al. 2010). Finally, for the reference sites, we generated a random collision date/time within three days before or after the data collection date to ensure the provided date/time was not always during the day (when data collection occurred) and preserve the accuracy of the vegetation measurements, which likely change throughout the year for a given site.

To support this study, the ADFG deployed 60 necklace-style GPS transmitters on wintering moose using a mixture of ground- and helicopter-based darting methods starting in March of 2017 (IACUC Protocol No. 0032-2018-42). The GPS transmitters provided data on moose movements in the study area. We downloaded radio-collared moose location data via satellite link (VECTRONIC Aerospace GmbH, Berlin, Germany). As radio-marked moose mortalities were detected, the ADFG redeployed the retrieved GPS transmitters. We collected hourly location data from 77 moose (57 females, 20 males) between April 1, 2017 and March 31, 2018.

We received additional five-minute locations from 35 of the female moose when they entered an area of interest to our study. Of our moose transmitters, 30 were equipped with a feature that increased the fix-rate from one location per hour to one location per five minutes when a location was recorded within a predefined ‘virtual fence’, and then once a location was recorded outside of this area, the fix-rate returned to normal. In this case, we set the virtual fencing to surround the road system in areas where MVC rates were historically known to be highest (i.e., major highways and traffic corridors), which allowed us to collect finer scale relocation data when moose were more likely to cross a road (Fig. 3-3).

Using R software, we located each point at which one of these moose crossed a

road within the study area. With the spatial packages “sp” and “rgeos”, we created a line between each set of relocations and used the gIntersection function to find any point at which that line crossed a known road (Bivand et al. 2013). To account for the possible difference in time frame between the two transmitter types, we only recorded the first intersecting point from each set of relocations. We generated an equal number of reference points on the road system for comparison, but to ensure our reference points and crossing points were within the same boundary, we computed the 95% minimum convex polygons for each of the radio-marked moose and created a rectangular bounding box that included each polygon (Calenge 2006). Our reference point list was clipped to be within this area. Finally, we generated a random date/time between April 1, 2017 and March 31, 2018 for the reference sites.

For moose in our study area, snow presence and depth data are key factors influencing the seasonal density of moose within valleys where humans live as high snow depths in the mountains force moose into lower elevations (Rausch 1958, Modafferi 1988, Becker and Grauvogel 1991, McDonald et al. In Review). Because there was only one weather station within our study area and the location was not proximate to our study sites, we modeled snow presence for each day of the year using our collected MVC site snow presence data. We then used the resulting GAMM to predict snow presence for each of our MVC, moose crossing, and reference sites based on the day of the year they occurred (Wood 2004). Additionally, to approximate the variation in moose movement throughout the day, we calculated the solar altitude, the position of the sun in relation to the horizon, for the date/times of the MVC, moose crossing, and reference sites (Agafonkin and Thieurmel 2018). We previously found solar altitude to be a better

predictor than hour of the day for movement variation throughout the day, because the solar altitude at dusk and dawn overlap (McDonald et al., In Review). To approximate the spatial density of moose, we calculated hunter success rate per Uniform Coding Unit, areas within each GMU delineated by watershed, as a proportion of total permits issued based on ADFG harvest reports in the study area from 2013 to 2017, based on the assumption that hunters are more successful in areas where moose are more likely to occur (Grovenburg et al. 2008).

We expected moose to avoid more densely populated areas that typically exhibited higher traffic volumes and levels of development. To account for this, we extracted speed limit, average annual daily traffic (AADT), and road classification from ADOTPF spatial datasets to each MVC, moose crossings, and reference site (ADOTPF 2016, 2017*a*, 2017*b*). We also calculated the road-less volume, the sum of distances to other roads as described by Chen and Wu (2014), and the distance to the nearest building based on a spatial dataset obtained from the 2011/2012 Matanuska-Susitna Borough LiDAR and Imagery Project. Then, we extracted light reflectance from the 336-m resolution December 2012 Visible Infrared Imaging Radiometer Suite Day/Night Band image of artificial lighting presence (Elvidge et al. 2017).

We also expected land cover conditions to be related to moose presence. Thus, we used the 30-m resolution 2014 LANDFIRE Project Existing Vegetation Type spatial dataset to calculate the number of different land cover types, proportion of coniferous, deciduous, or deciduous-coniferous forest, and proportion of shrub or riparian cover within 1,250 m of each MVC, moose crossing, or reference site. Additionally, we calculated the presence and number of possible corridors within 1,250 m of each site

based on spatial datasets representing the railroads, electrical lines, bodies of water, and roads within our study area (Alaska Department of Natural Resources 1995, 2006, U.S. Geological Survey 1998, ADOTPF 2016). Then, we calculated the distance to the nearest fire-burned area and extracted the year that the burn occurred and the area of the burn as possible interacting effects based on a spatial dataset of burned area perimeters documented in Alaska between 1940 and the present (Alaska Interagency Coordination Center 2018).

To compare MVC and reference site data, we compiled vegetation height and verge depth measurements into an area measurement, based on computation and summation of the area measured within each 2 m sample, and an evenness measurement, based on the standard deviation of the area measurements. We compiled the original vegetation classes into 7 broader groups including tree, sparse shrub, dense shrub, grass, forb, bare, and mowed and calculated the proportion of each group across the verge. To account for road sinuosity, we clipped the road to within 1,250 m of the MVC or reference site and calculated the length of the resulting segments divided by the Euclidean distance between the endpoints (Girardet et al. 2015). Moose are expected to prefer crossing roads where terrain is level, so we calculated terrain ruggedness by taking the standard deviation of the elevation within 1,000 m of each site using 2 m resolution elevation data from the 2011/2012 Matanuska-Susitna LiDAR and Imagery project (Danks and Porter 2010). Finally, we calculated the visual range of the motorist based on the summation of the road width and the length of the verge with less than 2.5 m high vegetation.

We used forward stepwise variable selection to create GAMMs with binomial

error distributions for both moose presence on the road system and MVC risk (Wood 2004, Zhange 2016). For both models, we began the selection process with parameters we expected to approximate either the spatial density of moose presence across the study area or the temporal density of moose presence throughout the day or year. Each density approximation was tested using parametric and non-parametric methods, and the degrees of freedom for each non-parametric variable was chosen based on the methods of Wood (2004). To further improve the moose presence model, we added regional-scale parametric variables representing expected attractants and repellants such as land cover or the presence of features that may act as travel corridors or represent areas of high utilization by humans (McCance et al. 2015, Wilson et al. 2015). We used the regional-scale variables that we found in the best fitting moose presence model along with local-scale variables to improve the MVC risk model. We expected our local-scale variables to influence motorist visibility or moose presence such as road geometry and roadside vegetation measurements. We tested for collinearity among candidate variables using a Spearman rank correlation test and used a threshold of 70% for removal (Dormann et al. 2013). We ranked support for all models using Akaike's Information Criteria (AIC_c) and verified the best fitting models distributional assumptions based on Q-Q plots of the deviance residuals (Wood 2004). To develop possible mitigation strategies, we used the best fitting model for both moose presence and MVC risk to recalculate the event probability for each data point and then compared this to the event probability for each data point if the value of each manageable variable was manipulated to its extreme observed minimum or maximum.

RESULTS

On roads classified by ADOTPF as highway, major, or medium, we identified 509 crossing locations from 15 radio-marked male moose and 2,263 crossing locations from 43 radio-marked female moose. After removing reference moose crossing sites that were outside the area of the radio-marked moose' home ranges, we had a total of 1,941 points for comparison. Sorted by classification, 470 reference sites occurred on highway, 761 on major, and 710 on medium roads, as opposed to the 316 crossing sites that occurred on highway, 1,253 on major, and 1,198 on medium roads. Radio-marked moose crossings were clustered in time towards mid-day during the summer, but spread throughout the day during winter (Fig. 3-4). Table 3-1 outlines the descriptive statistics of the remaining moose crossing related covariates.

Our final model of moose road crossing risk, based solely upon density-related measures, included a non-parametric smoothed term for the longitude and latitude of each site, the predicted snow presence, and the solar altitude. We improved the road crossing risk model with the addition of our hypothesized development and transportation related repellants: AADT for 2017, road-less volume, distance to nearest building, and light reflectance. We further improved the model with the addition of the following land cover related attractants within 1,250 m: the proportion of deciduous-coniferous and coniferous forest and the number of different land cover types and number of adjacent corridor types. The adjusted coefficient of determination (R^2) for the final model was 49.3% with a deviance explained of 44.6%. We considered the effects of changing all the attractants and repellants to their minimum or maximum values to understand their impact on the probability of a moose crossing at the site [P(MC)] (Fig. 3-5). When we manipulated

AADT and light reflectance to their maximum values, the average P(MC) decreased 29.7% and 55.2% respectively. At highest road-less volume (i.e. areas with low road density) and lowest road-less volume, the average P(MC) increased 36.8% and decreased 44.9%, respectively. When the distance to the nearest building was at its maximum value, the average P(MC) increased 31.6%. When the number of corridor types present was four out of four, the average P(MC) increased 9.3%, and when the number of interspersed land cover types was only five out of eight, the average P(MC) decreased 25.3%. When we decreased the proportion of deciduous-coniferous forest to its minimum value, the average P(MC) decreased 34.0%, and when we increased the proportion of coniferous forest to its maximum value, the average P(MC) increased 18.6%. The model used to predict snow presence had an R^2 of 72.8% and a deviance explained of 67.5%.

Between August 2016 and November 2018, we were able to locate 400 MVC sites and collect additional data at 741 reference sites. Of the MVCs we located, 218 exhibited evidence of a collision. Our modeling attempts included 361 of the located MVCs and 684 reference sites following the removal of observations with missing values. When stratified by road classification as defined by ADOTPF, we observed 139 MVCs and 180 reference sites on highways, 123 MVCs and 161 reference sites on major roads, 57 MVCs and 115 reference sites on medium roads, and 42 MVCs and 228 reference sites on minor roads. Table 3-2 outlines the descriptive statistics of the remaining MVC related covariates.

Our final model of MVC risk based solely upon density-related measures included a non-parametric smoothed term for the predicted snow presence and the solar altitude. The addition of road sinuosity, area of the verge obstructed by vegetation, and

angle between the road and verge further improved the model. The adjusted R^2 for the best fitting model was 38.7% with a deviance explained of 33.3%. We considered the impact of managing each visibility measurement to its minimum or maximum value to understand the effect of each on the probability of MVC [P(MVC)] (Fig. 3-6). When road sinuosity was decreased to its minimum value (i.e. a sharp turn), the average P(MVC) increased 18.7%. When road sinuosity was at its neutral value of 1 (i.e. a completely straight road), the average P(MVC) decreased 2.9%. At the maximum value of road sinuosity (i.e. a winding road), the average P(MVC) decreased 35.8%. When the area of the verge obstructed by vegetation was decreased to its minimum value, the average P(MVC) decreased 14.6%. The effect of minimizing the angle between the road and the verge, leading to a steep upward incline, increased the average P(MVC) by 12.2%, while increasing this angle to its maximum, leading to a steep downward incline, decreased the average P(MVC) by 9.3%. A neutral angle of zero (i.e. a road surface even with the verge) also increased the average P(MVC) by 2.6%.

DISCUSSION

Our use of the spatial and temporal density variables in the moose road crossing model tested our hypothesis that our moose would be more densely populated in some areas than others and that moose would be more likely to cross roads during their crepuscular activity periods, especially during winter. We found support for these hypotheses, as have the findings of other studies (Seiler 2005, Dussault et al. 2006). We further added variables we assumed would attract or repel moose from the site. When their effects were tested with predictive modeling, high light reflectance and AADT were

found to be repellants and exploratory analyses demonstrated that road crossings were more likely to occur on minor roads. We found an increased proportion of deciduous-coniferous or coniferous forest within 1,250 m of the site acted as an attractant, and the opposite effect occurred with a decreased proportion of each forest type. These two land cover types are often cited as attractants with deciduous-coniferous forest acting as forage and coniferous forest acting as protection from deep snow and escape cover from intense solar radiation or predators (Danks and Porter 2010).

The presence of possible movement corridors (i.e., intersecting roads, railroads, water features, and electrical lines) and an increased number of land cover types influenced the probability of moose road crossings. These possible movement corridors could act as a funnel, guiding moose across roads as they travel the path of least resistance, and the number of interspersed land cover types may have a similar effect as moose travel along the ecotone between them (Hurley et al. 2007, Danks and Porter 2010, Cserkesz et al. 2013). Further study of resource selection would be helpful for delineating their effects on moose distribution in the area.

Our model of MVC risk also supported our previous work regarding the timing of MVCs in Alaska. In the Matanuska-Susitna Borough, MVCs are clustered in time near dusk and dawn, especially during the winter when the probability of snow presence is high. Moose are crepuscular and their dusk and dawn activity in winter coincides with the rush hours of human traffic (Steiner et al. 2014, McDonald et al., In Review). Moose in these areas used roads and other corridors more often when higher snow depths in the mountains forced them into the valleys where the majority of roads and human settlements exist (Del Frate and Spraker 1991). We did not need a smoothed term for the

spatial coordinates of each site in this model because our reference sites were based on the location of our MVC sites. Our additional variables influencing motorist visibility also supported our hypotheses.

Road sinuosity, the length of the road section divided by the Euclidean distance between the starting and ending points of the section, has been documented as a predictor for MVCs in past studies (Finder et al. 1999, Roger and Ramp 2009, Girardet et al. 2015). As road sinuosity decreases from one and the curvature of the road sharpens, the motorist's visibility decreases and the motorist's speed is likely to decrease. As road sinuosity increases from one, the motorist's visibility increases because the actual distance they are traveling is longer than the Euclidean distance (Girardet et al. 2015). As vegetation increased, further obstructing the area of the verge, visibility decreased. This effect may be less pronounced than sinuosity because motorists may drive slower when their visual range is obstructed (Jagerbrand and Antonson 2016). This phenomenon may also explain the influence of the angle between the road surface and the verge. As the verge becomes steeper and deeper, motorists visual range would increase while the likelihood that an animal would cross would decrease. Clevenger et al. (2003) found that animals were more likely to cross a road when the terrain was level. Simultaneously, a deeper and steeper verge may provide some cover for animals from motorists as they are scanning the road at eye level, while a steeper upward verge may funnel animals onto the roadway (Finder et al. 1999, Hurley et al. 2007).

The influence of visibility measures over land cover measures in the MVC model, in conjunction with the avoidance of high AADT and light reflectance by radio-marked moose, suggested a behavioral aspect that we may be missing in this analysis. The radio-

marked moose in our study have exhibited various strategies from year-round residence in urban areas to 50 km migrations to the mountains for summer (ADFG, unpublished data). The difference in mortality due to MVCs between these behavioral groups may be the missing link in our models. The influence of variables approximating moose density in time were important to both our models, and space and land cover variables were important predictors for moose crossing probability. Using the moose movement data we are collecting, we should be able to improve the power of our models by incorporating seasonal space use and habitat selection approximations.

Our best fitting models for moose road crossing and MVC risks incorporated the best available data and our initial set of variables approximated nearly every aspect of an MVC we could measure. However, the incorporation of more precise site-specific weather data in future research in this area may be warranted. Additionally, human dimensions aspects should also be included in future research. Knowing how many or which motorists were distracted before their collision with a moose would heavily influence the ability of transportation planners and wildlife managers to decrease MVCs in this area, because we could separate MVCs where motorists cannot see moose from MVCs where they could have possibly seen the moose if they weren’t distracted. Finally, having a better understanding of moose seasonal and spatial density in the area would be informative for future mitigation projects.

MANAGEMENT IMPLICATIONS

Transportation and urban planning should consider the impact of concentrated traffic and development on the wildlife in areas they plan to develop. Keeping

development centralized and traffic volumes high within urban areas, while keeping traffic volumes low in areas moose are more likely to inhabit, should reduce the number of MVCs. Our radio-marked moose, while captured near roads in winter, tended to avoid highly trafficked areas and areas characterized by development.

Factors contributing to MVC risk were related to the construction and maintenance of the road system. Future road development should focus on less curved roads to allow for better motorist detection and future roadsides should avoid steep upwards verges that can act as funnels for wildlife moving across the landscape. Roadside vegetation removal is recommended to increase motorist visibility and decrease possible moose attractants. Vegetation removal should not be scheduled during the peak growing season unless removal can be accomplished each year, otherwise, the nutritional value of the next year’s growth will increase (Rea 2003).

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TABLES AND FIGURES

Table 3-1. Descriptive statistics of moose crossing related covariates, including land cover (LC) components and their associated extraction buffer radii in parentheses (Deciduous-Coniferous is abbreviated to DC). The descriptive statistics have been subdivided into reference sites and radio-marked moose crossing sites.

	Reference Sites				Radio-marked Moose Crossing Sites			
Covariate	Min	Max	x	SD	Min	Max	x	SD
AADT (2017)	26.00	33283.00	4308.95	6025.69	26.00	29282.00	2193.58	2684.22
Speed Limit (mph)	25.00	65.00	48.30	9.51	25.00	65.00	47.30	8.10
Light Reflectance (nW)	0.24	141.66	7.82	15.98	0.20	119.90	4.25	8.17
Roadless Volume	22621.73	55828.46	31388.40	7625.11	22621.66	55788.51	31998.62	8309.12
Corridor Count	0.00	3.00	1.13	0.44	0.00	3.00	1.14	0.45
Distance to Building (m)	11.86	5683.94	336.78	741.65	9.70	3990.10	282.06	654.67
Distance to Water (m)	4.23	5305.28	948.97	836.66	10.26	5163.12	1015.38	894.96
Distance to Burn (m)	0.00	18007.86	5746.57	4271.82	0.00	15384.12	5896.47	4887.78
LC Components (m)								
LC Interspersion (250)	3.00	7.00	5.80	0.70	4.00	7.00	5.80	0.68
LC Interspersion (500)	4.00	7.00	6.35	0.65	5.00	7.00	6.48	0.60
LC Interspersion (1250)	5.00	8.00	6.88	0.40	6.00	8.00	6.97	0.30
DC (250)	0.00	0.64	0.17	0.12	0.00	0.66	0.23	0.15
DC (500)	0.00	0.59	0.17	0.11	0.00	0.59	0.23	0.14
DC (1250)	0.00	0.52	0.18	0.10	0.00	0.52	0.23	0.12
Coniferous (250)	0.00	0.80	0.24	0.14	0.00	0.81	0.26	0.14

Coniferous (500)	0.01	0.70	0.24	0.13	0.02	0.69	0.27	0.12
Coniferous (1250)	0.03	0.62	0.23	0.11	0.05	0.62	0.26	0.09
Deciduous (250)	0.00	0.60	0.15	0.11	0.00	0.52	0.16	0.11
Deciduous (500)	0.01	0.48	0.16	0.09	0.01	0.44	0.16	0.09
Deciduous (1250)	0.01	0.44	0.15	0.07	0.01	0.33	0.15	0.07
Shrubland (250)	0.00	0.88	0.11	0.14	0.00	0.89	0.10	0.14
Shrubland (500)	0.00	0.88	0.11	0.15	0.00	0.88	0.10	0.15
Shrubland (1250)	0.00	0.83	0.12	0.15	0.01	0.83	0.12	0.15
Riparian (250)	0.00	0.92	0.07	0.11	0.00	0.73	0.06	0.07
Riparian (500)	0.00	0.92	0.07	0.10	0.00	0.74	0.06	0.06
Riparian (1250)	0.00	0.81	0.08	0.09	0.00	0.59	0.08	0.07
Agricultural (250)	0.00	0.67	0.02	0.07	0.00	0.61	0.02	0.05
Agricultural (500)	0.00	0.53	0.02	0.06	0.00	0.51	0.02	0.05
Agricultural (1250)	0.00	0.38	0.02	0.05	0.00	0.37	0.03	0.07
Developed (250)	0.00	0.96	0.19	0.16	0.00	0.90	0.15	0.09
Developed (500)	0.00	0.76	0.15	0.14	0.00	0.74	0.11	0.08
Developed (1250)	0.00	0.45	0.12	0.10	0.01	0.43	0.09	0.07

Table 3-2. Descriptive statistics of moose-vehicle collision related covariates, including land cover (LC) components (Deciduous-Coniferous is abbreviated to DC). The descriptive statistics have been subdivided into reference sites and radio-marked moose crossing sites, as well as into field-derived and spatially extracted measurements (associated extraction radii in parentheses unless measurement is based on a single point extraction).

	Reference Site				Moose-Vehicle Collision Site			
Covariate	Min	Max	x	SD	Min	Max	x	SD
Average Angle of Verge (rad)	-1.04	1.00	0.19	0.31	-0.95	1.07	0.28	0.33
Vegetation Height Area (m^2)	6.30	93.00	66.11	18.27	5.80	91.50	56.45	18.42
Vegetation Height Evenness	0.08	6.26	1.88	0.35	0.32	4.14	1.85	0.37
Verge Depth Area (m^2)	-68.70	83.80	7.55	15.72	-57.80	91.40	12.29	16.40
Verge Depth Evenness	0.00	11.18	0.91	0.87	0.00	3.93	1.00	0.64
Road Width (m)	1.10	51.35	9.40	4.31	1.90	166.40	11.22	9.09
Visual Range (m)	7.60	86.06	27.85	14.28	11.90	184.40	34.70	15.10
Presence of Fencing	0.00	2.00	0.16	0.40	0.00	2.00	0.10	0.32
Presence of Snow	0.00	0.85	0.12	0.16	0.00	1.00	0.14	0.19
Presence of Adjacent Water	0.00	1.00	0.01	0.09	0.00	2.00	0.01	0.14
Presence of Adjacent Residential or Commercial Property	0.00	2.00	0.42	0.68	0.00	2.00	0.29	0.59
Proportion of Vegetation by Type:								
Tree (%)	0.00	0.90	0.48	0.31	0.00	0.90	0.37	0.26
Dense Shrub (%)	0.00	0.55	0.08	0.09	0.00	0.70	0.10	0.11
Sparse Shrub (%)	0.00	0.40	0.02	0.05	0.00	0.35	0.02	0.04
Forb (%)	0.00	0.45	0.03	0.06	0.00	0.65	0.04	0.08
Grass (%)	0.00	1.00	0.07	0.13	0.00	0.95	0.09	0.16
Bare (%)	0.00	0.35	0.04	0.06	0.00	0.60	0.06	0.08
Mowed (%)	0.00	0.60	0.01	0.05	0.00	0.70	0.02	0.06
Spatially Extracted (m):								
Sinuosity (1250)	0.03	2.05	0.80	0.33	0.03	1.50	0.96	0.19

AADT (2017)	26.00	29282.00	3612.87	3889.18	26.00	28559.00	4155.34	4950.64
Speed Limit (mph)	20.00	65.00	49.40	10.96	25.00	65.00	51.88	9.66
Light Reflectance (nW)	0.23	123.59	4.61	9.25	0.22	67.74	4.05	7.29
Roadless Volume	22620.49	99052.75	37141.42	18056.07	22680.06	99822.71	38158.16	19019.10
Elevation (500)	0.22	428.89	38.68	47.23	0.45	497.61	37.40	47.57
Distance to Building (m)	6.98	3592.15	213.23	438.84	9.92	5303.59	282.04	557.28
Distance to Water (m)	10.91	3677.14	853.96	667.79	0.00	4068.61	875.58	679.76
Corridor Count	0.00	3.00	1.08	0.40	0.00	2.00	1.11	0.42
LC Interspersion (1250)	6.00	8.00	6.80	0.44	6.00	8.00	6.83	0.43
Coniferous (1250)	0.04	0.56	0.25	0.10	0.06	0.54	0.25	0.10
Deciduous (1250)	0.03	0.46	0.18	0.07	0.05	0.46	0.18	0.07
DC (1250)	0.01	0.51	0.21	0.09	0.02	0.52	0.21	0.09

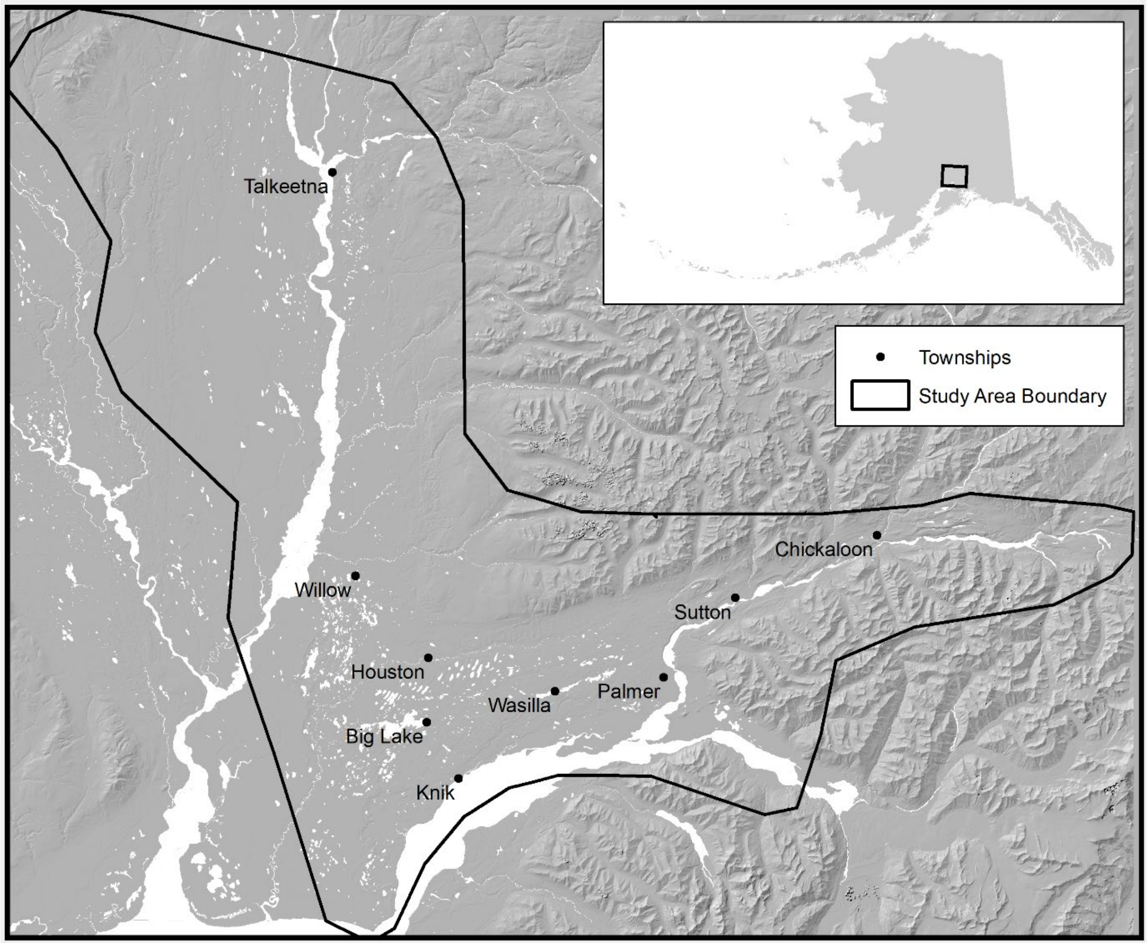

Fig 3-1. The Matanuska-Susitna Borough study area in south-central Alaska, USA. Our study encompassed the south-central area of this borough, between 149.7-151.1°N longitude and 61.2-62.5°W latitude, which contained the highest density of human inhabitants.

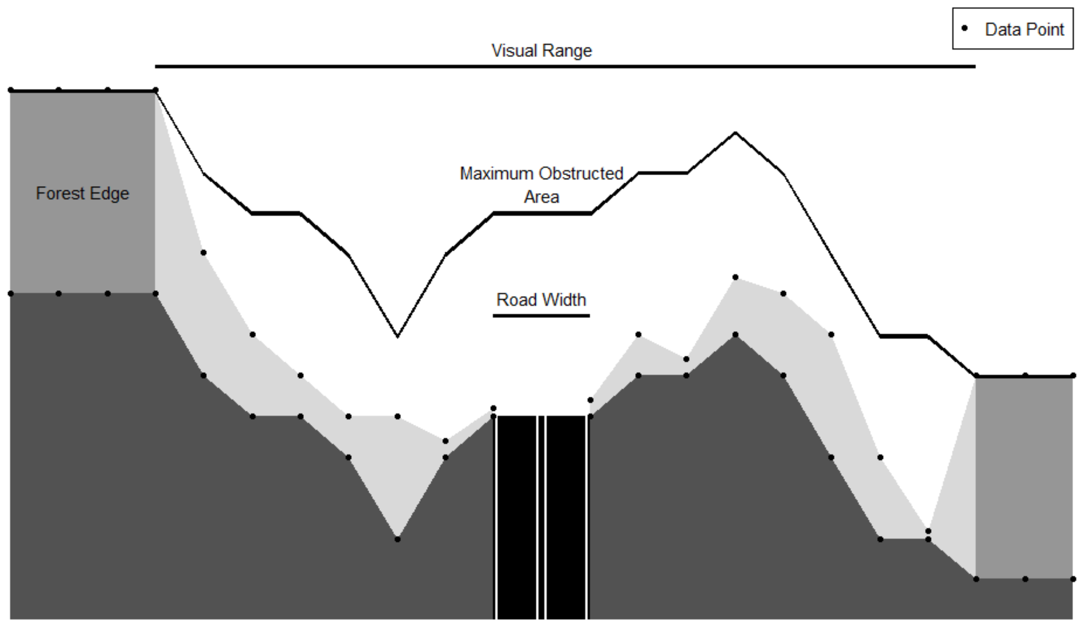

Fig 3-2. Site-specific variables recorded from roadsides at documented moose-vehicle collision (*Alces alces*) sites and reference sites in the Matanuska-Susitna Borough of Alaska, USA, August2016 – November 2018.

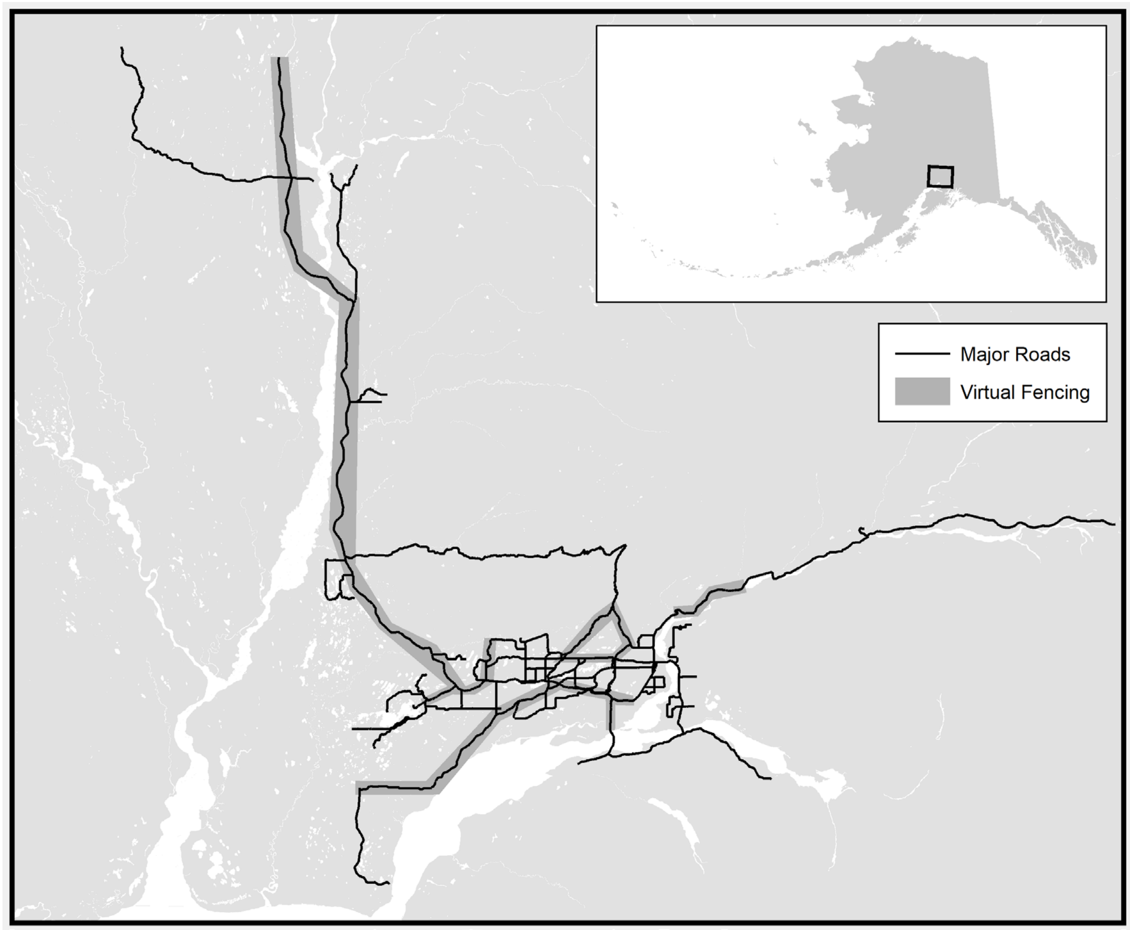

Fig 3-3. The 'virtual fence' feature equipped on 30 of our GPS transmitters increased the number of relocations recorded from one per hour to one per five minutes when the radio-marked moose (*Alces alces*) entered predefined areas of interest. Our areas of interest were chosen in areas where moose were more likely to be involved in a moose-vehicle collision based on historical data from this area of the Matanuska-Susitna borough of Alaska.

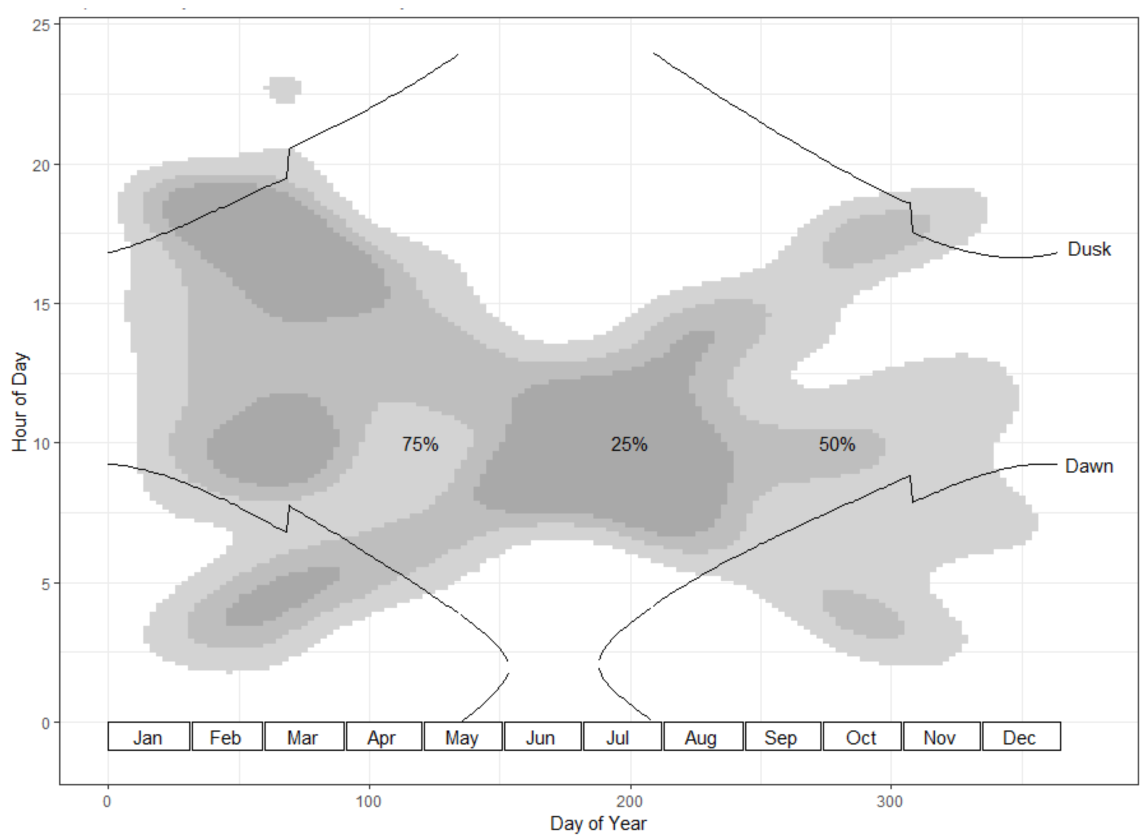

Fig 3-4. The temporal clustering of radio-marked moose (*Alces alces*) road crossings in the Matanuska-Susitna Borough of Alaska, USA, April 1, 2017 to March 31, 2018.

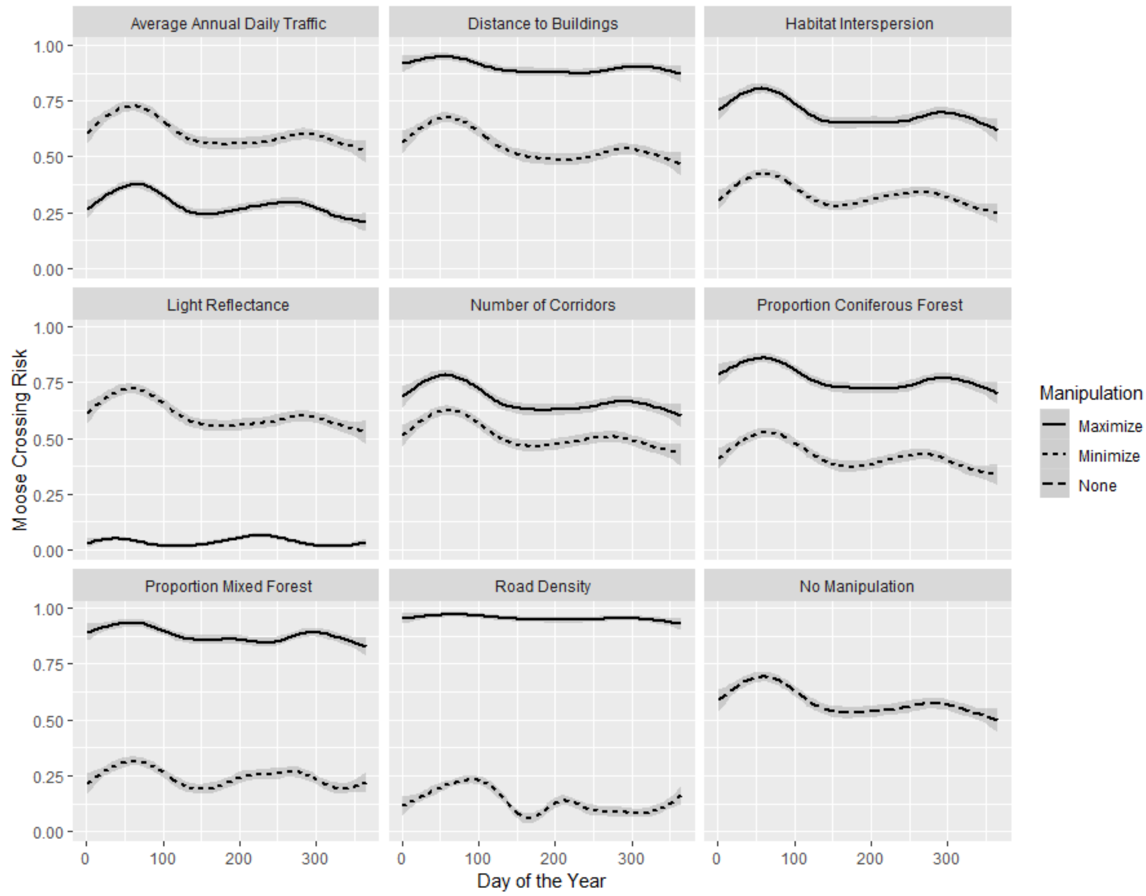

Fig 3-5. To understand the influence of habitat and development related features in our model of moose (*Alces alces*) road crossing risk, we manipulated each variable to its associated maximum or minimum value and used the final model of moose road crossing risk to predict a new event probability based on this new manipulated dataset. The average change was compared to an event probability calculated based on the original dataset.

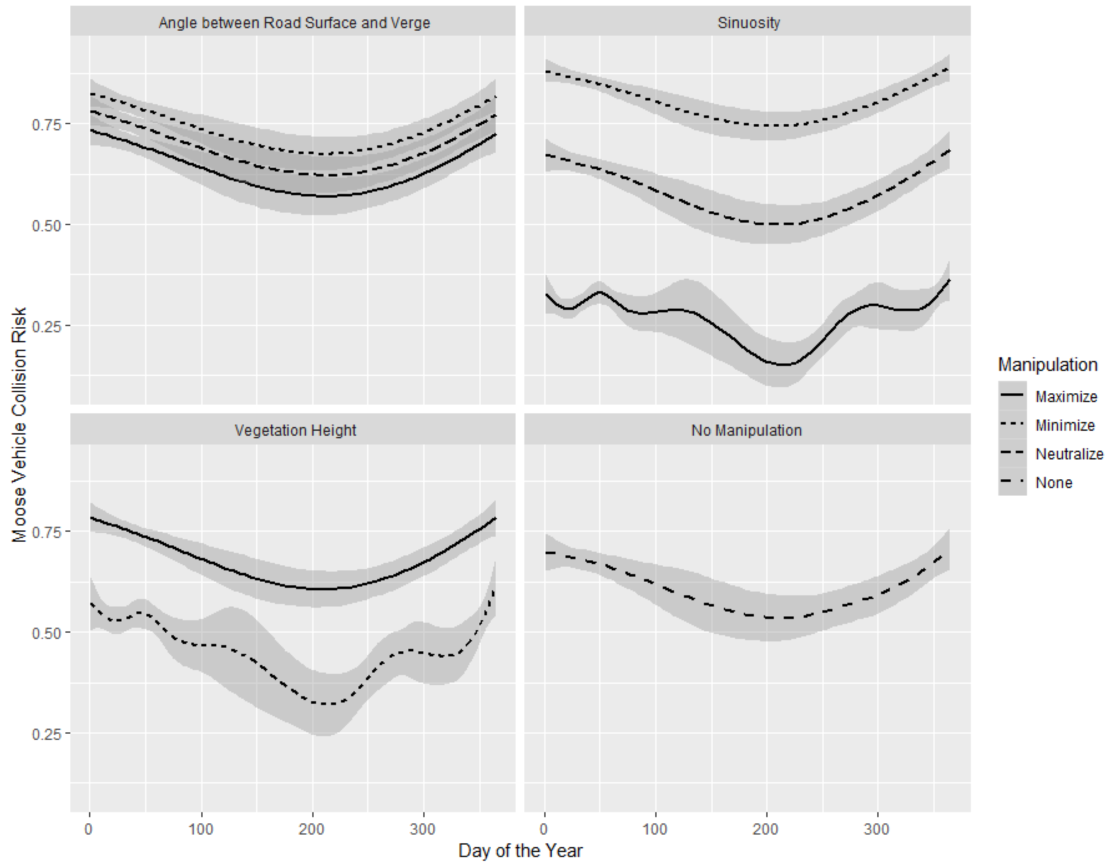

Fig 3-6. To understand the influence of the road measurements in our final model of moose-vehicle collision (*Alces alces*) risk, we manipulated each variable to its associated maximum or minimum value and used the final model of moose-vehicle collision risk to predict a new event probability based on this new manipulated dataset. The average change was compared to an event probability calculated based on the original dataset. For road sinuosity and the angle between the road surface and verge, we also included a neutralized manipulation. Here, a maximum value for the angle between the road surface and the verge reflects a steep downward verge, a neutral value reflects an even surface, and a minimum value reflects a steep upward verge. The minimum value of sinuosity represents a sharply curved road, a neutral value represents a straight road, and the maximum value represents a winding road.

CHAPTER 4

CONCLUSION

Throughout Alaska, moose-vehicle collisions (MVCs) are an ongoing problem for motorists, and as the area continues to see net population growth, the problem is unlikely to mitigate itself. Through historical records of MVCs in Alaska, we were able to see a common theme of increased MVC rates during winter in the four major population centers where this problem is concentrated. These winter peaks were especially common during the commuter rush hours, which coincide with the dusk and dawn activity periods of moose. We observed a noticeable difference between the MVC rates of the Matanuska-Susitna and Kenai Peninsula Boroughs and the Anchorage Municipality and Fairbanks-North Star Borough that could be attributed to artificial lighting, which was on average much higher on roads within the latter two areas where winter MVC rate increases were less pronounced.

Winter increases in MVCs are common in the literature, and various mitigation strategies have been employed. Seasonal signage treatments that led to observance of the speed limit were shown to decrease MVC rates (Sullivan et al. 2004). Seasonally decreased or more strictly enforced speed limits could also serve as a way to increase driver detection rates. Finally, I recommended transportation planners work together with wildlife management agencies and mobile mapping services, such as Google Maps, to increase driver awareness and alertness during periods of increased MVC risk in areas where the problem is heavily concentrated.

To further explore the local and regional factors contributing to MVC risk, I

analyzed the difference between spatially extracted or field-derived roadside characteristics of documented radio-marked moose crossing locations, reported MVC locations, and their associated reference locations. The radio-marked moose within our study avoided crossing roads at locations where traffic volume, road density, and artificial light reflectance were high, but they tended to cross at locations near buildings. They were also more likely to cross at areas where multiple corridor types were present and land cover interspersion was highest. In terms of land cover types near the road, our radio-marked moose tended to cross roads where the surrounding proportion of deciduous-coniferous forest and coniferous forest were both highest.

MVCs within our study area tended to occur on highways or major roads, which our radio-marked moose typically avoided. Road sinuosity, area of the verge obstructed by vegetation, and the angle between the road and the verge were the best predictors of MVC risk. When road sinuosity was low (i.e., at sharp curves), motorist detection distances would be minimal, increasing the chance that they would not be able to stop before hitting a crossing moose. When the area of the verge obstructed by vegetation was high, the amount of visible scanning distance decreases, so motorists are more easily caught off guard by incoming moose. When the angle between the road and the verge was high, the motorist is less likely to see the moose entering the roadway

More research is needed to improve these models, as the deviance explained by each was lower than expected. Weather data is very difficult to get in the area, and future research plans should try to account for this by actively collecting data or retrieving climatological models from other agencies. Human dimensions aspects should also be explored further. It would be helpful to know how many people are not reporting MVCs

and why, as well as how much they would be willing to pay to stop MVCs, since they are only a portion of total road accidents. Moose are a highly valued species in the area, but because the perceived density of them is so variable between stakeholder groups, it is difficult to determine the importance of the loss of a moose outside the legal definition of its value. Hopefully, the information I have presented here will help guide future transportation and urban planning, but more work is warranted to fully realize a mitigation plan for MVCs in the Matanuska-Susitna Borough and Alaska at large.